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USING MONTE CARLO SIMULATION TO IMPROVE CARGO MASS ESTIMATES FOR INTERNATIONAL SPACE STATION COMMERCIAL RESUPPLY FLIGHTS

by

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To resupply the International Space Station (ISS) with the items to support continuous human occupation and hardware to maintain system functionality, scientific experiments are necessary to maximize its potential as a world-class research laboratory. The transition of this function to the commercial sector under Firm Fixed-Price contracting has forced both NASA and commercial providers to adjust to make this effort successful. Improving bag-level cargo launch manifests delivered from NASA to the provider more than a year in advance is an area where significant gains can be realized by reducing, if not eliminating, costly and time-consuming analysis and/or physical rework during the launch campaign. The current process for developing these early manifests relies heavily on the experience and judgment of subject-matter experts to hand-build them for every flight. This research investigates the application of Monte Carlo simulation based on historical launch cargo data as a proof-of-concept demonstration for improving these manifest deliverables. The Monte Carlo simulation–derived manifests were checked against two dedicated ISS resupply missions, yielding promising results proving the concept. With further development, this methodology will be particularly useful in designing and implementing new cargo spacecraft.

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USING MONTE CARLO SIMULATION TO IMPROVE CARGO MASS ESTIMATES FOR INTERNATIONAL SPACE STATION COMMERCIAL RESUPPLY FLIGHTS

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ABSTRACT

To resupply the International Space Station (ISS) with the items to support continuous human occupation and hardware to maintain system functionality, scientific experiments are necessary to maximize its potential as a world-class research laboratory. The transition of this function to the commercial sector under Firm Fixed-Price contracting has forced both NASA and commercial providers to adjust to make this effort successful. Improving bag-level cargo launch manifests delivered from NASA to the provider more than a year in advance is an area where significant gains can be realized by reducing, if not eliminating, costly and time-consuming analysis and/or physical rework during the launch campaign. The current process for developing these early manifests relies heavily on the experience and judgment of subject-matter experts to hand-build them for every flight. This research investigates the application of Monte Carlo simulation based on historical launch cargo data as a proof-of-concept demonstration for improving these manifest deliverables. The Monte Carlo simulation–derived manifests were checked against two dedicated ISS resupply missions, yielding promising results proving the concept. With further development, this methodology will be particularly useful in designing and implementing new cargo spacecraft.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

ASI	Italian Space Agency
ATV	Autonomous Transfer Vehicle
c.g.	center of gravity
CLA	coupled loads analysis
CMC	Cargo Mission Contract
COTS	Commercial Orbital Transportation Services
CPAF	cost plus award fee
CRS	Commercial Resupply Service
CTB	cargo transfer bag
CTBE	cargo transfer bag equivalent
ESA	European Space Agency
FFP	firm fixed-price
HTV	H-II Transfer Vehicle
ISS	International Space Station
JAXA	Japanese Space Exploration Agency
L-	launch minus
LEO	low earth orbit
LOE	level of effort
LSM	Logistics Single Module
M-bag	Multi-Purpose Logistics Module bag
MDL	middeck locker
MIO	Mission Integration and Operations office
MIPD	Multi-Increment Planning Document
MOI	moment of inertia
MPLM	Multi-Purpose Logistics Module
MR	manifest request
MRM	Mini-Research Module
MTBF	mean time between failure
NASA	National Aeronautics and Space Administration
ORB-(number)	Orbital flight

RFP	request for proposal
RpK	Rocketplane Kistler
SARJ	solar alpha rotary joint
SpaceX	Space Exploration Technologies Corporation
SpX-(number)	SpaceX flight
SRMS	Shuttle Remote Manipulator System
SSRMS	Space Station Remote Manipulator System
STS	Space Transportation System
TBA	trundle bearing assembly
VLC	verification loads cycle

EXECUTIVE SUMMARY

Resupplying the International Space Station (ISS) with the supplies necessary to maintain continuous human inhabitation, maintain system functionality, and maximize the scientific research potential of the orbiting outpost is a critical task that has been recently transitioned from the National Aeronautics and Space Administration (NASA) to commercial providers SpaceX and Orbital Sciences Commercial Resupply Services (CRS) contract. NASA delivers bag-level manifests to the providers more than a year in advance to facilitate the providers' integration and mission design efforts. NASA has historically taken the approach of providing bag manifests where all of the cargo bags of a given size are predicted at the historic average for that size. This approach complicates the providers' preparation of the spacecraft, the completion of critical engineering analyses, and the development of mission related products as these bag-level manifests are not representative of the ultimate flight manifest. The result is a time-consuming, iterative process consisting of multiple exchanges between the NASA and provider subject matter experts with incremental changes to ensure that the desired manifest can be accommodated and that the related flight analyses and product are valid.

Given that the manifest is not even notionally defined at the time of these early deliverables, and that it would change in response to terrestrial or on-orbit events if it were, tools or methodologies that can improve the accuracy of the early predictions may result in significantly streamlining the process for both NASA and the CRS providers. This study investigated the application of Monte Carlo simulation for developing the early launch manifest deliverables as a proof-of-concept demonstration for quantifiably constructing bag-level manifests based on the historical mass distributions for each of the standard bag sizes as well as the total passive cargo mass for the dedicated ISS cargo resupply spacecraft.

The ISS cargo manifesting process is very dynamic, with changes driven by a number of factors including on-orbit events such as hardware failures and

changing consumption rates, and terrestrial factors such launch date slips, vehicle failures, and shifting management priorities. This study addresses those challenges by developing Monte Carlo simulations based on over 13 years of as-flownSS resupply cargo data. This methodology is demonstrated to a proof-of-concept level with the comparison of Monte Carlo derived bag-level manifests against NASA's historical approach of using uniform bag-mass distributions and ultimately the actual, as-flown manifests for two fully manifested resupply flights.

The Monte Carlo derived manifest methodology shows promising results for more accurately predicting the individual bag masses and the distribution of bag masses for bags of the same size within the manifest complement. It also provides a tool for the subject matter experts determine quantifiably where the predicted total cargo mass for any given flight is relative to the historical data and the ability to project this mass with some level of certainty. This tool will be especially useful as existing spacecraft cargo configurations and bag complements change and as new cargo spacecraft are developed.

While yielding positive results, the simulation, as constructed in this research, is limited and somewhat outdated. Further development is warranted with a few modifications to address some of the weaknesses. These include (1) updating the underlying data to more accurately reflect the current resupply needs as ISS has transitioned from the assembly phase to the research and utilization phase, (2) analyzing dedicated ISS resupply flights to determine the most appropriate distributions for the most populous bags in the manifest complements, and (3) developing a user-friendly interface that enables quick manifest generation and encourages acceptance by the subject matter experts.

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Completion of any project of substance is often the result of contributions, large or small, directly or indirectly, from many people, and this work and my studies at the Naval Postgraduate School are no different. I am especially grateful to those mentioned here for their guidance and support.

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I. INTRODUCTION

The arrival of the Expedition 1 crew of William Shepherd, Sergei Krikalev, and Yuri Gidzenko at the International Space Station (ISS) on November 2, 2000, began the longest period of continuous human presence in space, 15 years and counting at the time of this writing (Dunbar 2010). It also brought the requirement for regular resupply of food, spare parts, and scientific experiments required to sustain this remote human presence and perform meaningful, scientific research on a unique orbiting platform. The approach to human spaceflight has shifted over those 15 years and that has changed how NASA seeks to meet those objectives. With the desire to reinvigorate long-stalled efforts to develop a commercial-based spaceflight industry and the lure of dramatic cost reductions, NASA has committed to having private industry to take over routine tasks in Low Earth Orbit (LEO), including developing and operating spacecraft capable of resupplying ISS. The most visible evidence of this transition has been the retirement of the Space Shuttle Program and the awarding of Firm-Fixed-Price contracts to private companies to launch astronauts and perform cargo resupply services for ISS.

The transition from traditional government-led, Level-Of-Effort (LOE) and Cost Plus Award Feed (CPAF) to FFP contracting has required both NASA and its industry partners to adapt. NASA human spaceflight program managers were accustomed to a standing army workforce provided by CPAF contracting that was highly responsive to late changing requirements, evolving program objectives, and emerging technical challenges. Companies operating under FFP contracts seek to minimize technical modifications and analytical iterations in order to minimize cost, often performing only point solution analyses. Unless specific provisions are written into the contract, this often puts government program managers and FFP contractor at odds and can result in expensive contract modifications.

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II. COMMERCIAL SPACE AND ISS

The idea of commercializing space has been around since almost the advent of spaceflight itself. The emergence of the telecommunications satellite industry in the years following Sputnik's launch in 1958 is an oft-cited example of the successful realization of commercialization opportunities in the Space Age. In reality, however, most of this success did not occur until the 1970s, when the U.S. government changed its approach to managing the developing technology (Launius 2014). In the 1980s, space commerce got perhaps its biggest boost from the Reagan administration. The Presidential Directive on National Space Policy in 1988 referenced the aforementioned advancements in commercial satellites and launch vehicles as a basis for now prohibiting NASA from operating an expendable launch vehicle program, thus requiring NASA to procure launch services from commercial providers (Office of Press Secretary: White House 1988). The promotion of commercial space continued through the Bush and Clinton administrations as they issued guidelines and policies expanding required procurements to include any needed commercially available space-related technology, prohibiting NASA from acting as a deterrent to commercial space activities, and fostering commercial development by providing access to U.S. government space-related hardware, facilities, and data (Launius 2014).

A. ISS AS A CATALYST

Space commerce has been a primary objective for a United States-sponsored space station since from its inception. With his 1984 State of the Union address, then-President Reagan set forth his vision for a space station and for developing the commercial space industry:

> America has always been greatest when we dared to be great. We can reach for greatness again. We can follow our dreams to distant stars, living and working in space for peaceful, economic, and scientific gain. Tonight, I am directing NASA to develop a permanently manned space station and to do it within a decade.

> A space station will permit quantum leaps in our research in science, communications, in metals, and in lifesaving medicines which could be manufactured only in space. We want our friends to help us meet these challenges and share in their benefits. NASA will invite other countries to participate so we can strengthen peace, build prosperity, and expand freedom for all who share our goals.
>
> Just as the oceans opened up a new world for clipper ships and Yankee traders, space holds enormous potential for commerce today. The market for space transportation could surpass our capacity to develop it. Companies interested in putting payloads into space must have ready access to private sector launch services. The Department of Transportation will help an expendable launch services industry to get off the ground. We'll soon implement a number of executive initiatives, develop proposals to ease regulatory constraints, and, with NASA's help, promote private sector investment in space. (Reagan 1984)

The formative US-sponsored space station adopted stimulation of the commercial space market as a primary objective almost immediately. In 1987, NASA's publication of "Space Station: Leadership for the Future" by Franklin Martin and Trent Day identified the following beneficial areas of the space station (Martin and Day 1987):

- enhance capabilities for space science and applications
- stimulate advanced technologies
- promote international cooperation
- develop the commercial potential of space
- challenge the Soviet lead in space stations
- contribute to American pride and prestige
- stimulate interest in science and engineering education
- provide options for future development

ISS went from conceptual design to reality over the following two-and-a-half decades. When the major assembly was completed, the ISS program had to adjust its strategic goals to align with NASA's vision of operating ISS as a

premier research laboratory. In 2012, ISS Program Manager Michael Suffredini (2012) presented the following updated strategic goals:

- maximize science and technology research and development on the ISS to realize its full potential
- achieve operational and cost efficiency with a high performance ISS team working in an optimal and inclusive program structure
- raise awareness of the ISS, its relevance and benefits in our daily lives and our future
- provide global leadership, strategic alliances, and partnerships to fully utilize ISS capabilities to further research and exploration
- demonstrate capabilities that benefit space exploration and expand our reach beyond Low Earth Orbit (LEO)
- use the ISS to catalyze commercial development and operations in space

Many of the objectives changed to reflect the changing geopolitical environment; however, the goal of using ISS to stimulate the commercial development in space remained constant.

A number of government programs and initiatives were established to foster the commercial space industry and to build more efficient public/private partnerships with the ultimate goal of shifting NASA from developer and operator for LEO transportation services to consumer. These efforts were formalized with the passage of the Commercial Space Act of 1998 by the 105th Congress. Section 101 of this law deals specifically with the commercialization of the ISS including:

> The use of free market principles in operating, serving, allocating the use of, and adding capabilities to the Space Station, and the resulting fullest possible engagement of commercial providers and participation of commercial users will reduce Space Station operational costs for all partners and the Federal Government's share of the United States burden to fund operations.

Despite this, the market was slow to develop, hindered by high risk, high barriers to entry (development costs), low potential for profitability, and delays in

ISS launch and assembly. Critical momentum was finally achieved when President George W. Bush unveiled his Vision for Space Exploration in 2004 that directed NASA to pursue access to ISS by commercial means for both crew and cargo (NASA 2004).

B. COMMERCIAL ORBITAL TRANSPORTATION SERVICES PROGRAM

Although ISS resupply was a growing concern, it was not until the Space Shuttle Columbia accident in 2003 and the resulting plan for the Space Shuttle’s retirement that efforts to address this issue seriously began. With the loss of the Space Shuttle’s cargo capability, a shortfall of sufficient resupply to meet the needs of ISS was predicted that would be exacerbated after the conclusion of the European Space Agency’s Autonomous Transfer Vehicle (ATV) program in 2014 (NASA 2014).

In 2006, NASA awarded funded Space Act Agreements (SAA) to the Space Exploration Technologies Corporation (SpaceX) and Rocketplane Kistler (RpK) through the Commercial Orbital Transportation Services (COTS) Program (NASA 2003). The COTS Program was charged with establishing a new way of partnering between the government and private industry and the use of funded SAAs provided the mechanism to allow the industry partners to develop LEO spacecraft and launch systems without requirements of traditional Federal Acquisition Register (FAR) based procurements. The SAA’s defined a milestone-based payment schedule that shifted the financial risk of cost overruns from NASA to the provider. One important criterion for selection was that the potential industry partners have sufficient financial resources and make a substantive investment in their effort. NASA, in fact, ended its SAA with RpK in October 2007 after they failed to meet required financial milestones (NASA 2013). NASA opened a second round of competition to fill the vacancy left by the removal of RpK that resulted in selection of Orbital Sciences Corporation (Orbital) (NASA 2008a).

The structure of the SAAs gave NASA the latitude to work with SpaceX and Orbital to develop their spacecraft and to complete integration activity ensuring they satisfied all of the ISS safety and compatibility requirements for berthing to ISS. The COTS program culminated with successful demonstration missions to ISS by SpaceX's Dragon spacecraft in May of 2012 and Orbital's Cygnus spacecraft in September of 2013.

In addition to the two funded SAAs, NASA awarded several unfunded SAAs to encourage the larger space industry to continue development of space transportation services with the goal of growing a pool of the available providers for future services and solicitations.

C. COMMERCIAL RESUPPLY SERVICES CONTRACT

In December 2008, NASA awarded $3.5 billion FFP contracts to SpaceX and Orbital for a combined 20 resupply missions (12 for SpaceX, 8 for Orbital) (NASA 2008b). Unlike the COTS SAAs, this award was issued under the FAR Part 12 Acquisition of Commercial Services, which requires that the commercial item or services that meet the agency's need is available and that it can be procured when the agency needs it. Originally planned to be competed after the successful completion of the COTS demonstration missions, the procurement was accelerated to minimize the gap between the Space Shuttle's retirement and the availability of the Commercial Resupply Services.

Both SpaceX and Orbital experienced delays of approximately two and half years during the COTS Program that, in turn, delayed the start of ISS resupply in earnest under the CRS contract. NASA took care to stock ISS appropriately to cover the resulting gap between the last Space Shuttle flight (STS-135/ULF-7) in July 2011 and the first CRS flight (SpX-1) in October 2012. Any potentially critical resupply issues during this gap were mitigated flights of ESA's ATV in March 2012 and Japan's H-II Transfer Vehicle (HTV) in July 2012 and, to a lesser extent, the COTS demonstration flights.

D. RESUPPLYING ISS: A BRIEF HISTORY

The task of keeping ISS adequately supplied is complicated by the need to maintain the delicate balance necessary to maintain astronaut health and spacecraft system functionality while maximizing scientific research. Although it seems like a straight forward process on the surface, it is actually a highly nuanced, labor-intensive process that requires diligently managing competing objectives and evolving management priorities. In order to put this challenge into context, it is necessary to understand the entirety of the ISS cargo resupply process, including how NASA packs cargo for launch and return, the spacecraft used to deliver it, and the manifesting process for determining what cargo is ultimately launched on a particular flight.

1. Cargo Bag Types and Packing

a. Standard Cargo Bags

NASA launches and returns the majority of its cargo to and from ISS in soft-sided Nomex bags. There are seven standard sizes of cargo bags: cargo transfer bags (CTBs), which come in four sizes: Half, Single, Double, and Triple CTBs, and Multi-Purpose Logistics Module (MPLM) bags (M-bags) in three sizes: M-02, M-01, and M-03. The differing nomenclature is a remnant of their heritage and the platform on which they were originally flown, but they are essentially the same in construction.

CTBs were originally designed to fly in the Space Shuttle crew compartment and were required to fit through the Space Shuttle/ISS docking adapter. The Single CTB was designed to fit in Shuttle's Mid-Deck Lockers (MDL) and has evolved to the baseline volumetric unit of measure for the ISS program, that is the volume available on a spacecraft to carry pressurized cargo to or from ISS or volume available for stowage onboard ISS is measured in cargo transfer bag equivalents (CTBE) as opposed to cubic meters, for instance. For volume accounting purposes, 1 Shuttle MDL = 1 cargo transfer bag equivalent (CTBE) with these terms being used interchangeably during the overlap of the

Space Shuttle and ISS Programs. Half, Double, and Triple CTBs are all sized relative to the Single CTB (i.e., two Half CTBs can fit into a Single CTB, two Singles into a Double).

M-bags were designed to accommodate the larger cargo required for ISS systems and research; however, they share the same basic characteristics of CTBs. These bags were designed for launch and return in the MPLM which is berthed to one of the ISS berthing ports that provides a larger opening than the Shuttle docking adaptor. They are also measured in multiples of the Single CTB, with the M-02 equivalent to four CTBs, the M-01 to six CTBs, and M-03 to 10 CTBs. A common point of confusion regarding the M-bag naming convention should be noted as that they are not ordered in increasing size, (i.e., the M-02 bag is sized for four CTBE while the M-01 bag is sized for six CTBE). This is confusing, even for NASA personnel, and there is a proposal under consideration to eliminate the M-bag nomenclature and extend the CTB naming convention, (i.e., M-02s would change to four CTB bags, M-01s to six CTB bags, and M-03s to 10 CTB bags). For clarity, this thesis will list the bags using the current nomenclature in order of increasing volume; M-02 bags will appear before M-01 bags then M-03 and so forth.

A single point reference for cargo bags did not exist prior to 2009 when Eugene Schwanbeck of the ISS Program's Mission and Integration Office (MIO) compiled a one-page summary of bag types, dimensions, volumes, and maximum loading capacity that has become the working reference. Table 1 presents the physical dimensions and maximum load capabitlies of the standard cargo bags considered in this thesis with graphical representations in Figure 1.

Table 1. ISS Cargo Bag Types. Source: Schwanbeck (2009).

Bag Type	External Dimensions L x W x H [cm (in)]	Internal Dimensions L x W x H [cm (in)]	Max Load Kg (lb)	External Volume m^3 (ft^3)	Internal Volume m^3 (ft^3)	CTBE
Half CTB	24.8 x 42.5 x 23.5 (9.75 x 16.75 x 9.25)	24.13 x 41.28 x 22.86 (9.5 x 16.25 x 9.0)	13.62 (30)	0.025 (0.87)	0.023 (0.80)	0.5
Single CTB	50.2 x 42.5 x 24.8 (19.75 x 16.75 x 9.75)	49.53 x 41.28 x 24.13 (19.5 x 16.25 x 9.5)	27.24 (60)	0.053 (1.86)	0.051 (1.74)	1
Double CTB	50.2 x 42.5 x 50.2 (19.75 x 16.75 x 19.75)	48.26 x 41.28 x 46.99 (19.0 x 16.25 x 18.5)	54.48 (120)	0.106 (3.78)	0.096 (3.31)	2
Triple CTB	74.9 x 42.5 x 50.2 (29.5 x 16.75 x 19.75)	72.39 x 41.28 x 46.99 (28.5 x 16.25 x 18.5)	81.72 (180)	0.159 (5.64)	0.144 (4.96)	3
M-02	89.7 x 53.34 x 50.8 (35.3 x 21.0 x 20.0)	87.0 x 52.1 x 49.53 (34.25 x 20.5 x 19.5)	90.8 (200)	0.243 (8.58)	0.227 (8.0)	4
M-01	89.7 x 53.34 x 81.8 (35.3 x 21.0 x 32.2)	87.0 x 52.1 x 80.72 (34.25 x 20.5 x 31.78)	136.2 (300)	0.391 (13.8)	0.368 (13.0)	6
M-03	89.7 x 53.34 x 133.3 (35.3 x 21.0 x 52.5)	87.0 x 52.1 x 132.0 (34.8 x 20.5 x 52.0)	227.0 (500)	0.637 (22.5)	0.623 (22.0)	10

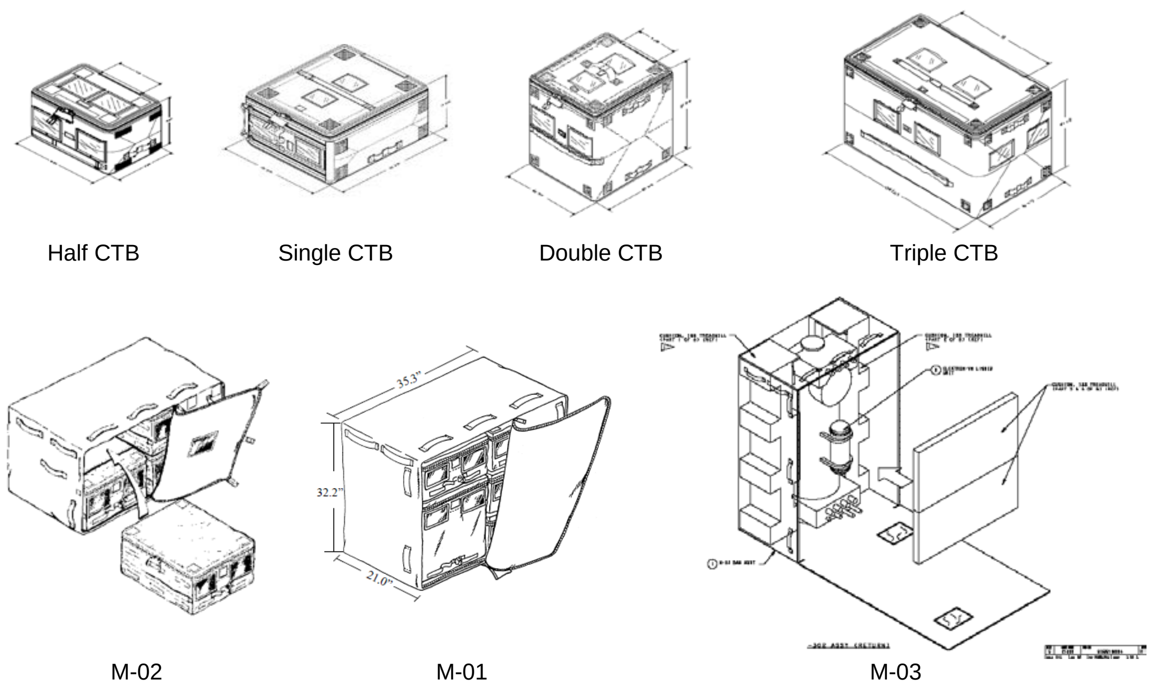


Figure 1. Illustrations of CTBs and M-bags. Source: Schwanbeck (2009).

b. Other Cargo Types

Other methods are used to launch and return cargo having special or unique requirements that cannot be accommodated by the soft-sided bags described above. Active and passive scientific research experiments can be flown in powered or unpowered lockers that are physically hard-mounted within the pressurized compartment of the spacecraft. Biological or other scientific samples that require thermally-conditioned transport are flown in rigid, insulated bags that are conditioned with passive cooling or warming bricks. The mass of the cargo items launched using these methods are typically much more predictable than the other bag types are so not be considered in this thesis.

Large hardware that exceeds the dimensions or mass capability of the standard M-bags may be flown in a foam “clamshell” custom built for that item. The need for this is infrequent and is usually negotiated with the spacecraft provider as it arises during the launch campaign; therefore, those situations are not addressed in this thesis.

c. Packing Considerations

Several factors must be considered when preparing and packing cargo for launch. In nearly all cases, multiple cargo items are packed within a single bag. Aside from matching cargo items with the appropriately sized bags, items to be packed together must be compatible as not to induce any safety hazards or potentially damage other items. With these constraints satisfied, two overarching approaches can be taken to pack the hardware. The first approach is to pack for spacecraft volume efficiency where the contents of each individual bag is maximized, regardless of where those cargo items will be stowed or used on-orbit. This method increases the overall mass to orbit, but can require extensive on-orbit crew time to break down the bags and distribute the cargo across ISS.

The second approach packs CTBs and M-Bags with like items or items that are stowed or deployed in close proximity on ISS. This method nearly always results in lower bag density; however, what this method sacrifices in cargo mass

efficiency is offset in on-orbit crew time and stowage efficiency. The preferred method has alternated between these two approaches over the life of the ISS depending on the prevalent issues and ISSP management objectives of the day. Regardless of the approach, changes late in the manifesting process can have a profound effect on the bag-level manifest.

2. Resupply Vehicles

NASA has sustained ISS through the years using a variety of spacecraft including those developed and flown from its international partners, and most recently, private industry. The following is a brief description of these spacecraft and their capabilities.

a. The Space Shuttle

The Space Shuttle was the centerpiece of the United States' space program for 30 years. By the Space Shuttle Program's conclusion in 2011, it had completed 37 missions to ISS delivering major elements for assembly or providing logistics and experiment resupply. While the tendency is to think about pressurized cargo being carried in the Shuttle crew cabin, the relatively small cargo volume (approximately 128 CTBE) was primarily dedicated to supplies supporting the Shuttle crew, sortie experiments, and contingency hardware and only provided limited supplies for ISS and its crew. More substantial resupply is necessary to support continuous human occupancy was provided by two pressurized elements that were flown in the Shuttle's payload bay: the Multi-Purpose Logistics Modules (MPLM) and SPACEHAB's Logistics Single Module (LSM).

(1) Multi-purpose Logistics Module

Three MPLMs were built by the Italian Space Agency (ASI) and provided to NASA. MPLM was the larger of the two platforms and primary method of Shuttle-based resupply and used for 11 of the 16 Shuttle-based resupply flights.
The MPLM was a stand-alone pressurized element with a cargo capacity of up to

9,000 kg that launched in the Shuttle's payload bay (NASA 2010). After the Shuttle docked to ISS, the MPLM was retrieved from the payload bay using either the Shuttle Remote Manipulator System (SRMS) or the Space Station Remote Manipulator System (SSRMS) and berthed to ISS on either Node 1 or Node 2 depending on the ISS configuration at the time.

(2) SPACEHAB Logistics Single Module

The SPACEHAB Logistics Single Module (LSM) was a much smaller platform, offering a contract value 2,700 kg of cargo capacity (NASA 2000). In contrast to the MPLM, the LSM attached to the Shuttle's crew compartment through a pressurized tunnel connected to the Shuttle airlock and Orbiter Docking System and served as an extension of the Shuttle's pressurized volume. The smaller size of the LSM allowed for larger unpressurized cargo to be flown in the payload bay compared to what was capable on MPLM flights. This allowed for balanced meshing of assembly and resupply on the only two LSM flights, STS-116/12A.1 and STS-118/13A.1, which delivered the P5 and S5 truss segments, respectively.

SPACEHAB's Double Module was another pressurized Shuttle-based resupply platform used early in the ISS program. As the name suggests, The Double Module was approximately twice the volume of the LSM. It was only utilized for two ISS flights, STS-101/2A.2a and STS-106/2A.2b, carrying cargo geared toward outfitting ISS in preparation for initial occupancy rather than for logistics resupply, and hence, will not be considered in this thesis.

b. Russian Progress Spacecraft

A version of the unmanned, expendable Russian Progress spacecraft has been providing logistics resupply to various space stations since its initial launch to Salyut-6 in 1978 (Wade 2014). With a regular launch schedule of three to four launches per year, it has been the metronome of ISS visiting vehicles. Progress offers a relatively limited cargo capacity of 1,800 kg per vehicle and provides

resupply for the ISS Russian crew members. NASA has purchased upmass (and disposal) capability on Progress vehicles as needed to augment the Shuttle resupply missions during the ISS assembly phase and the gap between the retirement of the Shuttle and operational commercial resupply. Progress also served as the primary resupply vehicle during the grounding of the Shuttle fleet in the wake of the Space Shuttle Columbia accident. No agreement to use Progress to resupply the United States segment of ISS currently exists; however, dedicated upmass may be negotiated on a case-by-case basis.

c. Autonomous Transfer Vehicle (ATV)

NASA added two expendable resupply vehicles operated by its international partners; the European Space Agency's (ESA) ATV and the Japanese Aerospace Exploration Agency's (JAXA) HTV to meet the resupply needs. These vehicles are considered to be under the umbrella of the United States Orbital Segment (USOS) of the ISS Program.

ATV was the largest vehicle in the ISS resupply fleet with a cargo upmass capability of over 7,600 kg comprised of up to 5,500 kg of dry cargo, 800 kg of water, 100 kg of Oxygen and Nitrogen gas, and 860 kg of refueling propellant [ISS ref 2010]. The pressurized cargo section of ATV was designed and built by ESA's contract partner Thales-Alenia Space, the same company that designed and built MPLM for ASI, and is based on the MPLM design. ATV autonomously docked to a docking port on the Russian segment similar to the Russian Progress vehicles. The ATV program concluded with the completion of it fifth mission to ISS in 2015.

d. H-II Transfer Vehicle (HTV)

JAXA's HTV is the second of the IP vehicles under the USOS umbrella and offers both pressurized and unpressurized cargo capability. The pressurized cargo capability is rated at 5,500 kg; however, it may be reduced for any given flight depending on the unpressurized complement (NASA 2010). The HTV was

the first free-flying spacecraft to be grappled by the SSRMS and is the model for the commercial resupply architecture.

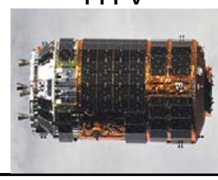
e. Dragon

In 2012, SpaceX's Dragon became the first commercially developed spacecraft to visit ISS and has since completed six missions to ISS under the CRS contract. Dragon has an advertised pressurized cargo capability of 3,310 kg and can carry a similar amount of unpressurized cargo (NASA 2010). Dragon's smaller volume and the historical cargo packing density typically results in actual cargo delivered to ISS of approximately 1,700 – 1,900 kg. Dragon is currently the only available U.S. spacecraft with the capability to return pressurized cargo safely to earth.

f. Cygnus

Developed by Orbital Sciences Corp., Cygnus is the second commercial spacecraft in the ISS resupply fleet. Its pressurized cargo module was designed and built by Thales Alenia Space and shares MPLM-heritage with ATV. Cygnus has an advertised pressurized cargo capability 2,000 kg, increasing to 2,700 kg with the Enhanced version beginning with the Orb-4 flight (Orbital 2013). Like Progress, ATV, and HTV, Cygnus is an expendable vehicle that disposes of trash and waste cargo via a destructive reentry. Note: Orbital Sciences Corp. merged with Alliant Techsystems (ATK) in early 2015 and change their corporate name to Orbital ATK. The CRS flight designations changed at that point with subsequent flights denoted with OA-. For the sake of consistency, this thesis will continue with Orb- designation; however, anyone performing additional research in this area is advised to look for the OA- flight identification beginning with OA-4. A summary of the USOS ISS resupply spacecraft is presented in Table 2.

Table 2. Summary of USOS Cargo Resupply Spacecraft Source: Dyson (2013).

Vehicle	ATV  ESA	HTV  JAXA	Dragon  SpaceX	Cygnus  Orbital
Approximate Cargo Upmass Capabilty (kg)	5,500	5,500	3,310	2,000 (Enhanced: 2,700)
Estimated Cargo Volume (CTBE)	230+	200-250 (Configuration dependent)	105	120 (Enhanced: 180)
Return/ Disposal	Disposal	Disposal	Return	Disposal
Unpressurized Cargo Capability	No	Yes	Yes	Non
Flights per Year	1	1	3-4	2-3
Notes	Ended in 2014		Dragon redesigned for the SpX-3 flight	Transitioning to Enhanced Cygnus at the Orb-4 flight

E. THE MANIFESTING PROCESS

Defining what cargo needs to be launched to ISS, and when, would ostensibly appear to be a relatively simple process. After all, consumption rates of consumable items such as food, water, and other crew provisions, and hardware items such as filters can be predicted. Mean Time Between Failure (MTBF) for system components can be estimated from analysis and testing. In practice, however, this is a complicated and dynamic process with a multitude of variables.

1. Determining the Cargo: A Simplified Overview

Determining which cargo to launch and return is handled through a complex and involved process that operates continuously over many months, managed by the MIO Office within the ISS Program. ISS cargo can be broken down in to three primary categories: consumables, systems hardware, and scientific research experiments ("utilization" in NASA vernacular). Small amounts of cargo for computer/network resources and Extra-Vehicular Activity (EVA), (spacewalks), are broken out as individual categories but tend to be quite small, comparatively. The organizations responsible for these areas are solicited semiannually for their launch mass projections for the calendar years extending out through the end of the ISS program.

The annual upmass projections are useful in determining how many flights are required for a given year and when they need to launch and can then be procured from the CRS providers. The available upmass is then allocated across the anticipated flight schedule for the respective year and documented in an internal ISS Program document titled the Multi-Increment Planning Document (MIPD). This is an iterative process that adjusts to changing flight schedules, updated vehicle capabilities, and ISS system performance.

Cargo mass allocations for each flight are frozen in the MIPD at L-7 months. From this point, it is the responsibility of the groups responsible for the various cargo categories to prioritize and manage the cargo they wish to fly within these allocations. The organizations submit Manifest Requests (MR) for each piece of cargo that is then reviewed and approved by representatives of the MIO office. The MIO office is responsible for ensuring that the requested cargo aligns with the planned activities and objectives on ISS for the corresponding timeframe. This is a highly dynamic and iterative process as on-orbit events and changing management priorities dictate. The number of changes to the cargo manifest tends to reduce as hardware delivery to the ISS packing contractor milestone approaches. Although changes may occur after hardware is delivered

if on-orbit events or other significant circumstances should warrant, it is not typical.

There are two, formal management checkpoints during this process, at L-3 months and L-6 weeks. At L-3 months, the cargo manifest is reviewed at a high level to ensure that organizations are utilizing their mass allocation, the manifested items align with ISS Program priorities for the timeframe, and identifying any issues with the schedules for delivering cargo to the packing contractor. Also, this is an opportunity for the hardware providers/stakeholders to request additional upmass or to relinquish upmass that they do not expect to utilize for re-allocation to other areas.

By L-6 weeks, all approved cargo should have been delivered to the packing contractor where it is processed and packed for flight under the Cargo Mission Contracts (CMC). The L-6 week review serves as final management check that the responsible organizations have delivered the manifested cargo and that the spacecraft is being utilized to the fullest extent possible. This review also sets the cargo manifest baseline that will be evaluated for the series of ISS Program reviews of flight readiness preceding the ultimate Go/No Go decisions. This process is closed out as the packed bags are weighed and delivered to the CRS provider at L-30 days.

The preceding description and the flow chart shown in Figure 2 are simplified overviews of the manifesting process shown in Figure 2. Also as shown in Figure 2, multiple flights are being managed, concurrently adding to the overall complexity. This process has evolved with years of experience and is more involved in practice than can be presented here.

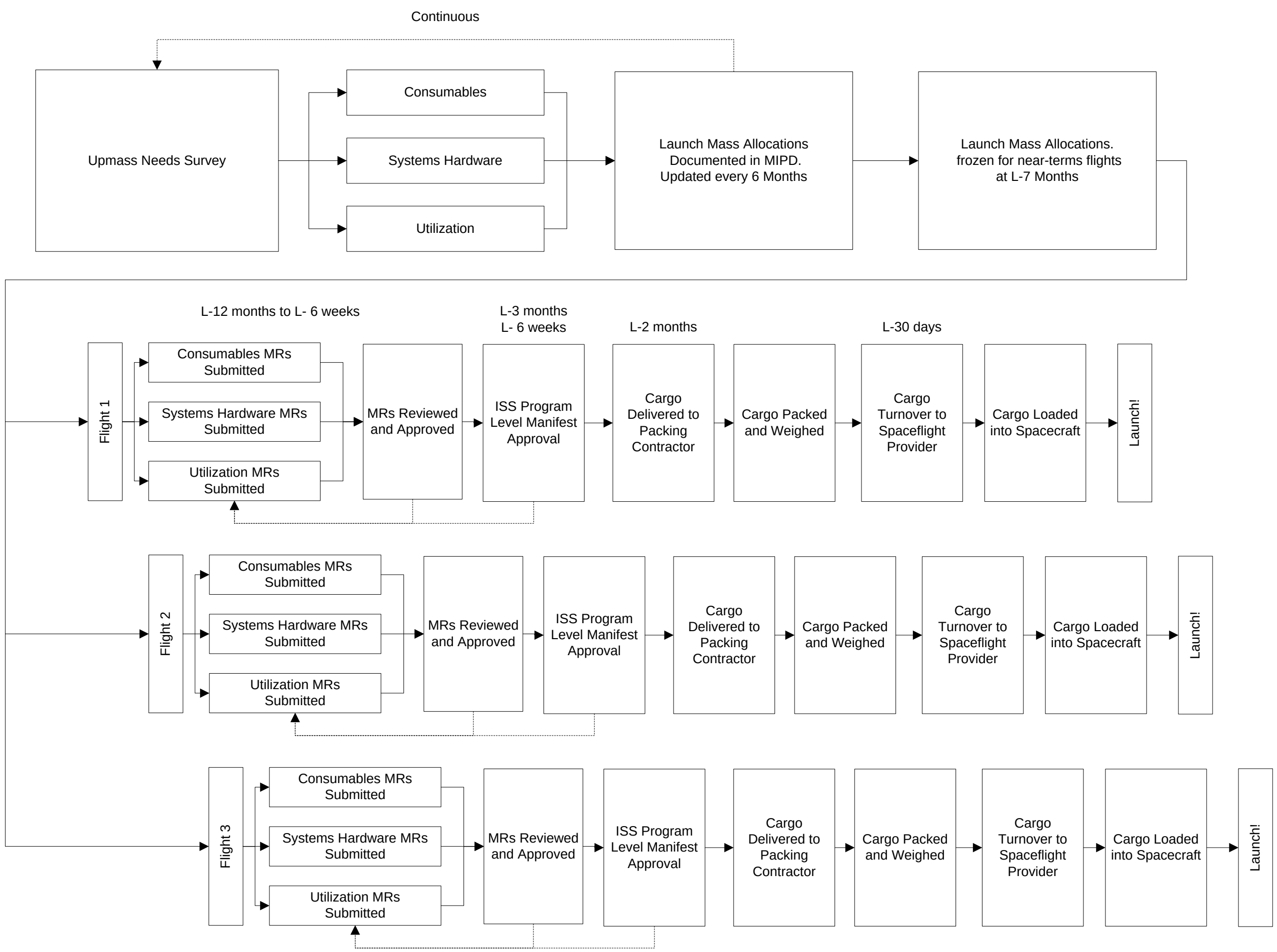


Figure 2. Simplified Manifesting Process Diagram

2. Bag-Level Manifest and Mass Properties

The primary cargo data deliverable from NASA to the visiting cargo vehicle providers is a bag-level manifest based on the number of each type and size of the cargo bags the specific vehicle can accommodate. This delivery includes the estimated mass, center-of-gravity, hazardous cargo information, and handling constraints for every bag in the complement. The unique designs of pressurized sections for the various cargo vehicles result in cargo bag complements that are specific to that vehicle. SpaceX's Dragon spacecraft, for example, has a more traditional capsule design to facilitate its reentry capability and requires more of the smaller bags to utilize effectively the available pressurized volume as a result. By contrast, without the aerodynamic requirements associated with re-entry and return, Orbital's Cygnus spacecraft's cylindrical design can accommodate more of the larger bag. The specifics of the bag complements for these two spacecraft will be discussed further in later sections.

a. Process Overview

NASA delivers the bag-level manifest to the visiting cargo vehicle provider at defined times during the launch campaign to support the providers' analytical and contractual milestones such as the Mission Integration Review and Cargo Integration Review. These milestones are often tied to critical points in the mission and flight design processes where the contractor must deliver acceptable mission designs, integration schedules, issue identification and resolution plans, etc.

Figure 3 presents a sample of the timeline for these data exchanges between NASA and a CRS provider. Again, this is a simplistic representation of a very involved process. While the general flow of this process is similar for all visiting cargo vehicles, there may be differences in the milestones or the L-minus timing of the data exchanges based on the needs of the vehicle provider. For example, since ATV and HTV are provided by other government space agencies

and launched from outside of the US, they have different requirements and were and are negotiated differently than CRS-contracted vehicles. Each vehicle provider may also have specific launch processing decision points or events such as hard ballasting, propellant or fluid loading that can also influence the data exchange schedules.

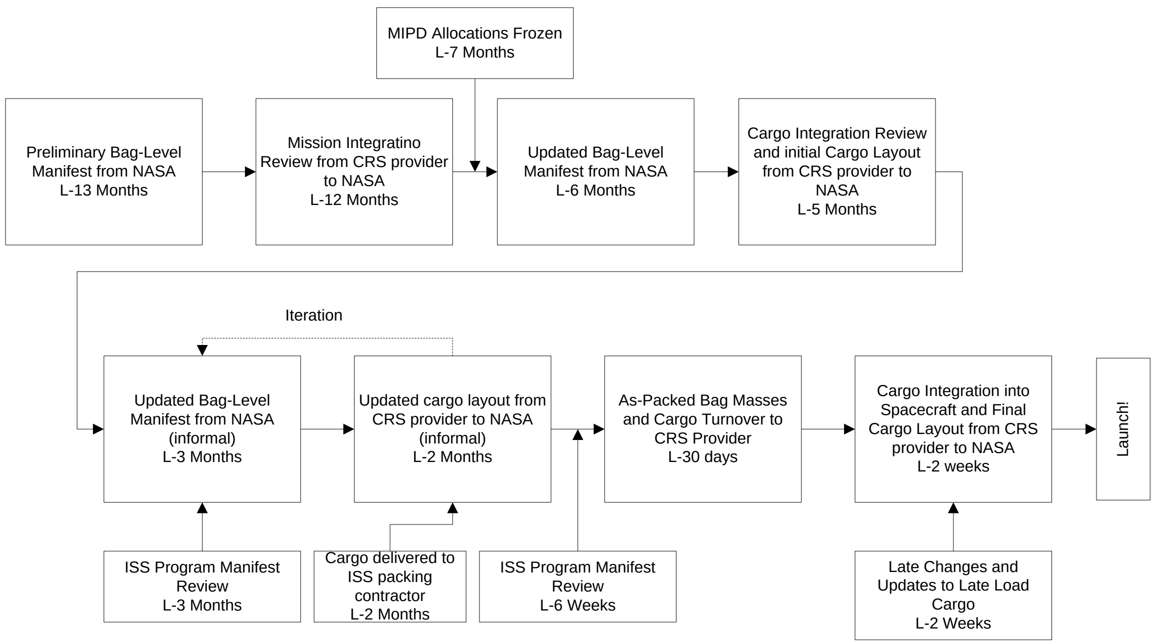


Figure 3. Sample Bag-Level Manifest Mass Properties Timeline

The execution of the CRS contracts has highlighted the importance of these data exchanges and both NASA and the CRS providers have adjusted to include more informal deliveries outside of those formally defined in the contracts. There is mutual benefit to increasing the frequency of these exchanges as providing the best available products minimizes potentially large discrepancies close to launch that could ultimately limit what and how much cargo can fly. This is represented in Figure 3 by the iteration loop between the L-3 month and L-2 month milestones; however, iterative data exchanges may occur at many places throughout the process. Since the undertaking of this thesis, NASA has agreed to increase the number of bag-level manifest deliverables to CRS providers at L-13 months, L-7 months, L-5 months, L-3

months, L-6 weeks, L-30 days (actuals), and L-2 weeks (Late Load cargo updates only) with final verification at L-24 hours. The result is a more labor-intensive process for both NASA and the contractor, beyond what was originally envisioned and closer to what existed with previous government-provided spacecraft.

b. Bag Mass Property Estimates

Very little of the intended cargo is known when NASA is required to submit bag-level manifests at L-13 and L-7 months. In the early stages of the CRS contract, NASA took a simplified approach to estimating the bag masses in the bag level manifest. A quick analysis of the actual, as-packed data available at the time was performed and NASA calculated an average of 11 kg/CTBE. NASA later re-evaluated the data determined that the cargo flown in CTBs tended to be denser than that flown in the larger M-bags and the average density for the CTBs (halves, Singles, Doubles, and Triples) was closer to 13 kg/CTBE. Specifically, every bag of a given size was estimated to be at these calculated averages.I If 10 Half CTBs could be accommodated, all 10 would be estimated at 6.5 kg, all Single CTBs would be 13 kg, and so on. The estimated masses for the standard bag sizes using these two approaches is shown in Table 3.

Table 3. Bag Mass Estimates from Historical Averages

Bag Type	CTBE	Initial Bag Mass Estimates (11 kg per CTBE) kg	Modified Bag Mass Estimates (13 kg/11 kg per CTBE) kg
Half CTB	0.5	5.5	6.5
Single CTB	1	11	13
Double CTB	2	22	26
Triple CTB	3	33	39
M-02	4	44	44
M-01	6	66	66
M-03	10	110	110

NASA has occasionally taken an alternate approach of biasing the individual bag masses significantly higher than historical averages with the goal of preserving the ascent performance. This approach minimizes the risk of not being able to accommodate increases in the cargo mass; however, it introduces the risk of the actual cargo masses undershooting the projections. This is an equally undesirable outcome depending on the specific spacecraft sensitivities as that can result in the need to launch and return ballast material in usable cargo volume.

The fidelity of the bag mass estimates improves as the launch date approaches and more actual cargo is available to be assessed. At approximately L-6 months, approved hardware is pulled from the manifest database and preliminary bag layouts and corresponding bag masses are generated. From this point, the bag-level manifest mass-property estimation is a nearly continuous process. There will be a number of bags that are estimated to be full, some partially full, and some empty depending on the amount of approved cargo at the time. MIO personnel update the bag-level mass properties accordingly with the goal of preserving the highest degree of flexibility for manifest changes. This has historically been handled in an ad-hoc fashion with little quantitative assessment.

These updates are provided to the visiting vehicle providers at critical times as described in the previous section. Although the fidelity of the estimates improve as the launch date approaches, some level of uncertainly in the bag-level manifest exists until the cargo is actually delivered and the bags are packed, weighed, and transferred to the visiting cargo vehicle operator.

3. The Challenges of ISS Resupply

ISS visiting vehicle launches are scheduled two to three years in advance based on a number of orbital and terrestrial parameters such as solar beta angle, available launch windows, launch vehicle and spacecraft processing schedules, range availability, anticipated ISS docking or berthing port availability. The cargo allocations for any given flight are based on the projected needs of ISS and the

crew near the anticipated launch date. Several factors can drive changes in the manifesting process, and particularly late in the process that influence what cargo is ultimately launched or returned.

a. Launch Delays

Launch delays are a common occurrence in the space industry. They can be the result of many factors, some within the control of the launch provider or space agency, and some outside of their control. Unlike satellite launches or non-ISS Space Shuttle missions where the mission content does not change with launch date, launch delays can dramatically affect the resupply needs of ISS. The magnitude of the cargo manifest changes is dependent on on-orbit need, the length of the delay, and severity of any failures or other adverse conditions on ISS that may develop during the delay. For delays on the order of days, there will not likely be any impact to the cargo manifest. If, however, the launch slips several weeks or more, the manifest can change dramatically if on-orbit events warrant.

The scope of the potential changes is also a function the flight's position in the launch schedule. The changes may be minimal if the launch closely followed another resupply vehicle. If the launch closely precedes another resupply vehicle, cargo may be moved to that flight if the delay is anticipated to be lengthy and the cargo priority is high.

These types of changes were common during the Shuttle-era and the established analytical and operational processes that accommodated them with minimal impact. Transitioning to the CRS era post-Space Shuttle introduced new problems as the CRS providers were not prepared for the magnitude of the cargo manifest changes nor was NASA prepared for the sensitivities or limitations of new spacecraft.

b. Vehicle Failures

The loss of a cargo resupply mission can have a significant impact on ISS operations. The ISS Program's risk posture has been to protect for such failures by managing on-orbit inventories so that supplies do not fall below critical levels that could result in the exhaustion of supplies before the next resupply mission. This is referred to the "skip cycle" in NASA parlance. While this provides effective mitigation to sustain on-orbit activities, most cargo lost on the failed flight must be replaced and flown on subsequent flights. The impact on the subsequent flights depends on a number of factors including the flight manifest, specifically the proximity to the adjacent flights, the priority of the lost cargo, and the cargo already manifested on the subsequent flights.

Four of the 85 dedicated USOS and Russian resupply missions to date have failed to reach ISS: 44P, Orb-3, 59P, and SpX-7 (FPIP 2015). The failure of 44P in August 2011 was absorbed by the subsequent Russian flights, 45P and 46P and only minimally affected the manifest of the next USOS flight, ATV-3. The failure of Orb-3 in October 2014, however, resulted in a complete rework of SpX-5 and SpX-6 manifests. SpX-5 was approximately six weeks from launch at the time of the Orb-3 failure with nearly all of the manifested hardware delivered and ready to be packed. SpX-5 and SpX-6 were ultimately delayed for other reasons, providing the ISS Program with time to react and reprioritize cargo to sustain operations. Similarly, the unprecedented failure of back-to-back flights 59P and SpX-7 in 2015 greatly impacted HTV-5 and Orb-4, Orbital's return-to-flight mission. Additionally, the ISS Program was still recovering from the loss of nearly 2300 kg on Orb-3. Cargo for Orb-4 was packed to maximize volume usage and get as much cargo to orbit as possible, as a result.

c. Hardware Issues and Contingencies

Practitioners of systems engineering are familiar with "the bathtub curve" depicting a hypothetical system and/or hardware failure rate as a function of time. The curve gets its name from its elongated "U" shape with the steep side curves

at the beginning and at the end representing infant mortality/burn-in failures and lifetime/wear-out and the flat bottom section representing the normal operating life. Extensive ground testing and analyses are performed in an attempt to predict the system performance and expected operating life. Predicting the Mean Time Between Failure (MTBF) helps define the system component replenishment schedule; however, the microgravity environment of space affects systems' operating characteristics that can alter the predicted MTBF. For example, there may be higher number of start-up transient or infant mortality failures until the system performance in microgravity is better understood. The unpredictability of these types of failures can drive last minute changes to the pressurized cargo manifest. One notable example in the recent history of ISS that impacted the cargo manifest of the subsequent flight was the failure of the starboard Solar Alpha Rotary Joint (SARJ) in 2007.

There are two SARJ rotary joints on ISS that enable the solar arrays to track the sun in the alpha angle as ISS transits through its orbit. Any restrictions of the ability to maintain the solar arrays close to perpendicular to the sun will result lower power generations due to off-angle pointing thus limiting the available power to systems and experiment hardware. The starboard SARJ failure is an example of infant mortality exhibiting indications of a problem after only 83 days on orbit. The primary root cause was traced to insufficient lubrication for rolling contact surface of the Trundle Bearing Assemblies (TBA) that could have been identified and corrected prior to flight by repeating the testing that was was performed for the port SARJ. The corrective action was to lubricate the rolling surface and replace all 12 TBAs on the starboard SARJ (Harick 2010).

The impact relative to the work this thesis attempts to address was the late addition of 12 TBAs to the STS-126/ULF-2 flight manifest. A Single CTB packed with two TBAs averaged approximately 21 kg placing this in the 90th percentile of historical data for Single CTBs and 7 kg above the historical average. Six Single CTBs were required to launch the full replacement set of 12

TBAs for the starboard SARJ. The established analytical processes that existed during the Shuttle program made it fairly straightforward for this type of change to be accommodated and the bags were able to be divided with three being loaded in the MPLM and three in the Shuttle Middeck thus minimizing the impact to the MPLM. A similar change may not have been so straightforward for the CRS providers, however. This failure serves as an example of the type of high-consequence, high-priority hardware failures that can dramatically impact the cargo manifest.

d. Variable Consumption Rates

ISS has limited volume in which to warehouse supplies and critical spares so inventories are managed as close to the minimum acceptable levels as possible. The projected resupply needs are based on historical consumption rates. Slight variances in consumption rates or systems performance such as individual crew preference for specific food categories, water consumption, water recovery, decreased system performance, so these can alter the projected on-orbit need dates to protect the skip-cycle or maintain critical spares, that can change the relative cargo priority and ultimately affect the cargo manifest.

e. Missed On-dock Delivery

ISS systems hardware and research experiments are often very expensive, very complex, one-of-a-kind systems. Hardware is required to undergo extensive testing to ensure that all safety, operational, and performance requirements are met. In the case of most research experiments, they are often very specialized experiments developed by academia or scientific research organizations with limited budgets, minimal staffing, and little schedule margin. Any perturbations in development, production, or testing can delay the delivery to the cargo packing contractor by the required date. Missing this “on-dock” date often means being moved to a later flight and replaced with alternate cargo.

f. Shifting Management Priority

The structure of the ISS Program management is such that emerging political, international, or contractual issues may only be visible at the highest levels in the program and can only be traded against competing technical issues by high-level managers. Additionally, management focus tends to follow to the issues of the day. The magnitude of the changes are dependent on the number and severity of consequences of issues being considered. Again, it is hoped that the variability due to changes in management priority decreases as the CRS program matures and confidence in the ability to maintain flight schedules increases.

F. THE IMPORTANCE OF MASS PROPERTIES IN SPACECRAFT AND MISSION DESIGN

Mass properties are a fundamental element of spacecraft design and verification including: overall spacecraft mass, spacecraft center-of-gravity, moment-of-inertia structural verification.

1. Overall Spacecraft Mass

The overall spacecraft mass is a primary consideration for every aerospace program. The spacecraft mass is tightly coupled to the launch vehicle performance capability and can be a significant cost driver if a larger or higher performing launch vehicles are required. It is the systems engineer’s job to make the appropriate trades to allocate the available mass across the various systems, subsystems, and payload(s) to best ensure that the spacecraft can successfully complete its objectives within the available performance capabilities.

History shows that overall mass increases as the spacecraft design matures. Comparison of seven planetary spacecraft programs show an average of 27% increase in the spacecraft mass from ATP to launch (Brown 2002). Examples for human spaceflight include total mass growth of Apollo spacecraft from conception in 1961 until the final configuration in 1971 was 200%. There

was 25% dry mass growth for the Space Shuttle structure and thermal protection systems with 27% for the remaining Space Shuttle systems (Heineman 1994).

Initial mass estimates are usually a rough order of magnitude with some level of margin for allow for such growth. Mass estimates are tightly managed and accounted for through the design and assembly process to assure that performance measures are satisfied until the as-built mass is obtained when the completed spacecraft is weighed. In 2015, the American Institute of Aeronautics and Astronautics (AIAA) partnered with the International Society of Allied Weight Engineers, Inc. to publish S-120A-2015, Standard for Mass Properties Control for Space Systems and RP A-3, Recommended Practice for Mass Properties Control for Space Systems which, together, establish uniform processes for mass properties management during space systems development.

2. Center-of-Gravity

The center-of-gravity (c.g.), or the center-of-mass, is defined as a unique point around which distributed mass in a single rigid body or sum of masses in a multi-body system is balanced. The c.g. can be used to describe the motion of a rigid body or system using the translation of this point through space and the rotation around it. This a particularly important parameter for spacecraft as it influences spaceflight dynamics for stability and attitude control. The position of the c.g.can affect the size and placement of the spacecraft thrusters, thruster firing timing and durations, or performance of other methods of attitude control like gyroscopes. The spacecraft can improve performance by aligning thrust vectors as closely through the predicted c.g.as possible to maximize desired motion and minimize undesired motion and corrections. Knowledge of the spacecraft c.g. is also important to launch vehicles for structural analyses of loads to the mating adapters resulting from any offset from the launch thrust vector and/or other associated loads. Acceptable c.g. tolerances for launch vehicles or other interfaces such as common platforms or service modules are

usually defined in Interface Control Documents, Interface Requirement Documents and/or user guides.

3. Moment-of-Inertia

Moment-of-Inertia (MOI) is another mass property element that is important for spacecraft design. The MOI is can be simplistically defined as the resistance to rotation about an axis. The MOI is calculated through the summation of the mass elements times their distance from the three axes of the c.g. of the spacecraft. Knowledge of the MOI is critical for designing attitude control systems such as thrusters or gyroscopes to ensure that desired stability and maneuver requirements can be achieved.

MOI-ratio is often discussed in spacecraft design and recommends that the primary axis of rotation should be around the axis with the maximum MOI. This is most applicable to spin-stabilized spacecraft and not essential to this thesis.

4. Structural Loads Analyses

In addition to the more mission design related elements above, a changing cargo mass complement can affect the structural verification of the spacecraft and launch vehicle. The structural verification is a time consuming process that starts with analysis of the spacecraft/payload, the launch vehicle, and the quasi-static loads defined by the launch vehicle. The actual loads environment is a product of the integrated spacecraft and launch vehicle assembly; therefore, as the spacecraft mass properties change, analysis of the integrated assembly needs to be repeated. Larger mass payloads can increase the loads on the integrate payload/launch vehicle configuration. Analysis of this integrated assembly is called a Couple Loads Analysis (CLA). Historically, space programs perform at least two, if not three load cycles, as was the case with the Space Shuttle. Once the spacecraft design has matured and test validated models are available the final loads analysis, the Verification Loads Cycle (VLC) or Verification Loads Analysis (VLA), can be completed.

G. INTEGRATING THE CRS PROVIDERS

The CRS providers were able to develop their spacecraft under the COTS program using the traditional spacecraft systems engineering approach. Unlike traditional spacecraft programs, however, a high percentage of the overall mass, represented by ISS cargo in this case, is undefined until very late in the launch campaign. With Dragon for example, ISS cargo can comprise 40% or more of the spacecraft dry mass and up 30% or more of the overall spacecraft mass when including propellant and ballast. As described in the preceding section, both the contribution of the cargo to the overall mass and as well as the individual bag masses for distribution within the spacecraft are critical elements in mission design. Not knowing these with some amount of certainty until close to launch can be problematic, requiring late and hurried rework of verification and other associated mission products.

Flying out the remaining Space Shuttle missions was NASA's and the ISS Program's primary focus during the COTS program and the early stages of the CRS program. In the desire for simplicity and based on its experience with ATV and HTV, NASA only gave the CRS providers the maximum allowable bag masses for structural design and the historical averages for mission design. The actual dynamics and implications of the cargo manifest were an afterthought and absent of detailed discussion regarding the cargo manifest process and expectations; the CRS providers did not anticipate the variability in the cargo masses or the magnitude of changes that can occur late in the launch flow. The result was spacecraft with limited flexibility to accommodate dynamic cargo manifests.

At the same time, ISS Program managers were used to having virtually unlimited flexibility in deciding which cargo is launched and returned, including sometimes dramatic changes very close to launch. This was enabled historically by well understood vehicle performance, based decades of experience with the Space Shuttle, and supported by a standing army of analysts funded with CPAF

or Level-Of-Effort (LOE) contracts available to run a multitude of cases and 'what-if' scenarios.

By contrast, the FFP contracting approach for CRS was chosen, in large part, to lower the cost associated with spaceflight. To achieve that cost savings the CRS providers priced their services based on minimal analyses and certainly not the iterative or parametric efforts to which ISS managers had become accustom. In many cases they assumed single case, point solutions for complicated and expensive integrated analyses like the CLA.

For CRS, the "payload" for this analysis is comprised of the spacecraft, the pressurized cargo complement, and the unpressurized cargo complement. The standard CRS mission template calls for the CLA to be delivered to NASA between L-12 and L-10 months. Both the spacecraft and the unpressurized cargo complement are well defined at this point but the pressurized cargo complement is not. Any analyses performed in this timeframe would be based on the initial bag-level manifest provided at L-13 months. Since the loads and vibration environments are so tightly coupled with the payload mass properties, NASA's approach of providing uniform distributions of bag masses which are not representative of actual pressurized cargo manifest to be flown almost guarantees significant expensive and time-consuming re-work as the manifest becomes more defined.

H. AREAS FOR PROCESS IMPROVEMENT

The process described in Section C is comprised of many time-consuming, labor-intensive products that are often generated by hand by highly experienced engineers and coordinated among a wide array of technical and management teams. MIO personnel often find themselves at the fulcrum of competing technical and programmatic priorities while staying within the available capabilities of the CRS spacecraft. The success of the COTS and early CRS flights was largely attributable to the diligent work of dedicate teams outside of the original plan for the FFP CRS contracts. These flights, however, were flown

much lower than full capacity with the cargo being held artificially stable and were not reflective of the effort required for missions during the fully operational phase of the CRS contracts. The following are a few key areas associated with current process that can be improved and streamlined to effectively support an operational program with the real challenges of a dynamic cargo manifest.

1. Quantifying the Risk of Mass Estimates

The current process of providing the entire early cargo manifest with the historical averages results in a total cargo mass near the 60^{th} percentile, which is unlikely be reflective of the ultimate cargo manifest. This can lead to relinquishing upmass performance unnecessarily depending on the launch processing timelines and the responsiveness and flexibility of the CRS provider to react as the cargo manifest matures. MIO representatives may bias the estimates higher to preserve this performance but overestimating the launch mass has equally detrimental consequences. This has been done historically based on experience and intuition and without any quantitative assessment. Better quantitative understanding of actual as-packed cargo data through statistical analysis and simulations can substantially improve the initial and intermediate cargo mass estimates and streamline the interaction between NASA and CRS provider.

a. Initial Manifest Characterization

NASA had the luxury of virtually unlimited manifest flexibility through analytically intensive processes of the Space Shuttle program and other government-sponsored programs like ATV, HTV, and Progress. This methodology has, in essence, devalued the early manifest mass projections at the cost of analytical iterations throughout the mission design phase. NASA's decision to provide uniform bag masses by type for early CRS manifest deliverables at L-13 and L-7 months was based on this approach without consideration for the cost of iterative analyses incurred by CRS providers. Additionally, uniform bag mass distributions are not accurate representations of the final cargo manifest and limits the CRS providers' ability to manage

spacecraft mass properties and perform accurate verification analysis in a timely manner. This approach introduces the difficult trade between accepting unknown risk without performing additional, time-consuming analysis or NASA accepting the consequence of not launching needed cargo. Improving the early bag-level manifests to distributed profiles based on historical data and statistical probability will provide more realistic representation of the final cargo manifest that can result in a decrease number of bag masses that need to be reconciled as the manifest matures.

The CRS providers are required to fly a certain amount of scientific research cargo consisting of powered experiment lockers and passive conditioned stowage bags. Due to structural mounting interfaces, power and data connections, and time-critical access requirements, these items are nearly always co-located in a fixed location of the spacecraft. These items are also typically at or near the maximum allowable mass limits for their volumetric equivalents (Single and Double CTBs) and can significantly bias the spacecraft's c.g.and MOI. A uniform bag mass distribution does not allow the CRS provider to offset effectively the heavier research cargo and often results in "throw-away" work that needs to be repeated when the manifest is better characterized.

b. Intermediate Manifest Deliverables

Intermediate manifest deliveries, particularly between L-7 and L-3 months will consist of a combination of "known" bags based on the preliminary bag layouts provided by CMC and any remaining partially filled or unfilled bags. The current process is to estimate these bags relying on MIO personnel's experience, judgment, and interpretation of the potential cargo being considered. These deliveries occur near critical times in the spacecraft processing and mission design timeline and MIO personnel's estimates must balance the need to preserve as much available ascent performance as possible while not risking the need to fly high-density ballast. Probabilistic analysis of the manifest based on

historical data can provide higher fidelity estimates of the final cargo manifest and quantify the risk of high or low bag mass estimates.

2. Vehicle-Specific Manifesting

The current CRS Dragon and Cygnus spacecraft designs have distinctively different cargo bag complement capabilities and, as such, may be better suited to fly different types of cargo. For instance, Orbital's Cygnus spacecraft accommodates more M-bags than SpaceX's Dragon and therefore may be preferred to resupply food which is more efficiently packed in M-02s. By contrast, Dragon maximizes its useable pressurized volume using Half and Single CTBs and therefore may be better suited for smaller cargo items that are distributed throughout ISS. As more ISS resupply is performed under the CRS contract, vehicle-specific databases profiles can be constructed.

3. Limited Ability to Assess Manifest Changes

The uniform bag mass approach used by NASA for the early manifest deliverables translate into very generic spacecraft mass property budgets and conservative mission designs. This results in a very cumbersome and labor intensive process of coordinating manifest updates with the CRS providers. With limited insight into spacecraft performance characteristics, NASA has limited ability to assess various trade-offs as cargo moves on and off of a flight without engaging the CRS contractors. Although both companies have developed tools to facilitate NASA performing these trades independently, these tools are initialized using unrealistic, uniform bag masses initially provided by NASA. More representative bag-level mass predictions masses would result in higher fidelity mass property tools geared toward the actual flight manifest. This would enable MIO personnel to assess updates to the bag-level manifest by comparing preliminary, and proposed, layouts against the distributed layout accepted by the CRS provider at L-13 or L-7 months. For example, only deviations above an agreed-to threshold would require involvement of the CRS contractor team thus streamlining the process and benefiting both sides.

I. CHAPTER SUMMARY

The preceding sections in this chapter have described the spacecraft and processes used to resupply ISS with the necessary consumables and hardware to sustain a human presence and perform scientific research in LEO. The variety of spacecraft having different bag complements, dynamic terrestrial and on-orbit events, evolving launch schedules, and shifting management priorities make it difficult to accurate predict bag level cargo manifest and overall cargo mass for the missions early enough to support analytical analyses and mission design milestones. This has resulted in an inefficient, labor-intensive process that, without meticulous dedication, can result in undefined risk to NASA and or the CRS providers. All of this must occur between partners with differing objectives and clashing cultures under the pressures of firm, fixed-price contracts.

J. RESEARCH GOALS

The goal of the research documented in the thesis is to investigate the feasibility of utilizing Monte Carlo simulation to improve NASA's bag-level and total cargo mass predictions. Specifically, this research seeks to improve CRS performance by streamlining NASA/CRS contractor interaction during the manifesting process and improving CRS cargo carrying performance by:

- reducing the individual bag mass differentials between early manifests at L-13 and L-7 months, and the as-flown masses
- improving the accuracy of the predictions for total cargo mass estimated for CRS flights
- quantifying the risk associated with inaccuracy in the individual bag mass estimates by improving predictions through statistical probabilities

The cargo manifesting estimating process described previously is a labor-intensive process that relies heavily on individual expertise, experience, and hands-on management. It requires skilled leadership that can build successful teams composed of members from throughout the NASA and commercial organizations, and balancing competing objectives from a wide array of

stakeholders. The goal of this research is not meant to develop a solution that diminishes the value of these skills but rather to enhance the overall performance by exploiting the skills and experience by improving the methodology used for developing bag-level manifests thus alleviating the considerable overhead of coordinating manifest mass changes during critical periods. Additionally, focusing on a methodology based on a flexible, customizable tool that can be applied across the fleet of cargo resupply vehicles throughout the manifesting process will lead to greater acceptance by the user and management communities.

It is further intended that establishing a more detailed statistical understanding of the historical cargo mass distributions and trending will support optimization of cargo bag layouts by the CRS providers potentially minimizing sensitivities to mass variability. Confidence in NASA's ability to predict more accurately the final bag-level manifest may increase the CRS providers' willingness to perform parametric or variational analyses.

The following chapters of this thesis will describe exploring Monte Carlo simulation as a proof-of-concept for improving cargo mass predictions for ISS resupply flights SpX-3 and Orb-2. Chapter II will examine the application of Monte Carlo simulation to this problem based on historical data. Chapter III will test this approach by building specific Monte Carlo simulations. Chapter IV will apply the Monte Carlo simulation results to build bag-level manifests for the two CRS flights of varying bag complements and compare the accuracy of this method against a manifest using only historical averages with respect to the as-flown manifests. Chapter V will present conclusions that can be drawn from this study, recommendations for improving the Monte Carlo approach, and areas for future work on this subject.

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III. CARGO MANIFEST PREDICTION

The problem of accurately estimating the bag-level and overall cargo masses of ISS cargo manifests for CRS flights more than a year in advance of launch is challenging. NASA has historically taken the simplistic approach of just providing the historical average bag masses for the bag complements of the early visiting vehicles. This was not of much consequence at the time because these vehicles were provided by ESA and JAXA, governmental space agencies that have supported multiple analysis cycles as the cargo manifest matured during the launch campaign. Like any large bureaucracy, NASA did not want to deviate from methods that had proven to be successful. The CRS providers driven to offer the lowest prices under FFP contracts, however, did not budget for multiple analytical cycles to accommodate the changing manifests. Fortunately, increasingly powerful desktop computing tools can provide options to examine new approaches that can satisfy the needs of both sides. One such tool is Monte Carlo simulation.

The following sections of this chapter will present the ISS as-packed data on which this research was based, provide a brief history and description of Monte Carlo simulation, and further examination of the historical data in preparation for building the simulation.

A. HISTORICAL DATA

A substantial dataset of as-packed ISS cargo has been compiled over nearly 15 years of resupplying ISS. Data sets like this are ripe for evaluation and investigation for use in predicting future performance. Monte Carlo simulation is a technique that can take this data and apply it as the foundation for a mathematical model that can provide insight into the bag-mass distributions and generate the probability distribution for the overall cargo mass.

As mentioned in the Chapter I, all of NASA's ISS pressurized cargo is processed and packed for launch by CMC. The bag contents, layouts, and mass

property reports are documented on the CMC internal website and were retrieved and compiled for this study. All of the bag data for this study, both the flights comprising the data used for simulation analysis, as well as flights that occurred subsequent to the actual simulation construction, were retrieved from this site.

The data encompassed 29 flights, occurring over 13 years, and included ISS cargo launched on the Space Shuttle, ATV, HTV, Cygnus, and Dragon spacecraft. In addition to the dedicated cargo vehicles and platforms presented in Chapter I, cargo was launched in several of the pressurized elements that were permanently installed on ISS, namely, USOS elements Node 2 (Destiny), Node 3 (Tranquility), and the Permanent Maintenance Module (PMM), and the Russian Mini-Research Module 1 (MRM-1). A detailed list of the ISS cargo flights used in this research is presented in Table 4.

Table 4. ISS Cargo Flights. Adapted from NASA at www.nasa.gov.

Vehicle	Flight	Launch	Cargo Carrier
Space Shuttle	STS-102/5A.1	March 2001	MPLM
	STS-100/6A	April 2001	MPLM
	STS-108/UF-1	December 2001	MPLM
	STS-111/UF-2	June 2002	MPLM
	STS-114/LF-1	July 2005	MPLM
	STS-121/ULF1.1	July 2006	MPLM
	STS-116/12A.1	December 2006	SPACEHAB LSM
	STS-118/13A.1	August 2007	SPACEHAB LSM
	STS-120/10A	October 2007	Node 2/Destiny
	STS-128/ULF-2	November 2008	MPLM
	STS-128/17A	August 2009	MPLM
	STS-130/20A	February 2010	Node 3/Tranquility
	STS-131/19A	April 2010	MPLM
	STS-132/ULF-4	May 2010	MRM-1
	STS-133/ULF-5	February 2011	MPLM (PMM)
	STS-135/ULF-7	July 2011	MPLM
ATV	ATV-1	March 2008	ATV
	ATV-2	February 2011	ATV
	ATV-3	March 2012	ATV
	ATV-4	June 2013	ATV
HTV	HTV-1	September 2009	HTV
	HTV-2	January 2011	HTV
	HTV-3	July 2012	HTV
	HTV-4	August 2013	HTV
SpaceX	SpX-D	May 2012	Dragon
	SpX-1	October 2012	Dragon
	SpX-2	March 2013	Dragon
Orbital	ORB-D	September 2013	Cygnus
	ORB-1	January 2014	Cygnus

There were 1,863 of the standard CTBs and M-bags in this data set. The data was compiled and sorted by bag size. The mean and median bag masses were calculated for each bag size as well as the average mass per CTBE per bag size. The results are presented in Table 5.

Table 5. Historical Cargo Statistics

Bag Type	**CTBE**	**Number of bags**	**Historical Bag Mass Mean** Kg	**Historical Bag Mass Median** kg	**Average Bag Density** kg/CTBE
Half CTB	0.5	555	6.87	5.90	13.74
Single CTB	1	744	13.34	12.25	13.34
Double CTB	2	154	24.52	21.80	12.26
Triple CTB	3	154	36.05	34.80	12.02
M-02	4	104	51.48	46.62	12.87
M-01	6	138	63.67	61.54	10.61
M-03	10	14	108.1	92.63	10.81
Overall Average	--	--	--	--	12.27

These calculated averages support the estimates that MIO personnel made early in the COTS/CRS programs of 13 kg/CTBE for CTBs and 11 kg/CTBE for M-bags. While valuable in certain respects, simply knowing the mean and median is not sufficient in this case. Simply and uniformly using the average bag mass for every bag of a given size, however, is not representative of what the ultimate distributed bag mass properties are likely to be. Dr. Sam Savage of Stanford University discusses this effect in *The Flaw of Averages*. He postulates, simply stated, that fallacies arise when single numbers such as averages are used to represent uncertain outcomes. He continues that representing uncertain quantity with an average produces flawed results because it ignores the effect of inevitable variations ultimately under-estimating the risk or under-predicting the

result. Dr. Savage endorses Monte Carlo simulation as a solution this issue (Savage 2009).

B. MONTE CARLO SIMULATION

In contrast to deterministic analyses where all input parameters are treated as constants, probabilistic analyses like Monte Carlo consider input parameters as variable based on probability distributions. This has proven to be a highly effective way to account for variation and uncertainty. The term Monte Carlo is seemingly ubiquitous, everywhere from local church fundraisers to the most complex financial and technical analyses. It originates from the Monte Carlo region in the city-state of Monaco that is home to the iconic grand casino and its gambling image. The games in the casinos, and at the local Monte Carlo night, are relatively straightforward with known outcomes having known probabilities. Monte Carlo methodologies can be utilized to quantitatively “solve” much larger, more difficult, multi-parameter problems. The common thread is their basis on probability.

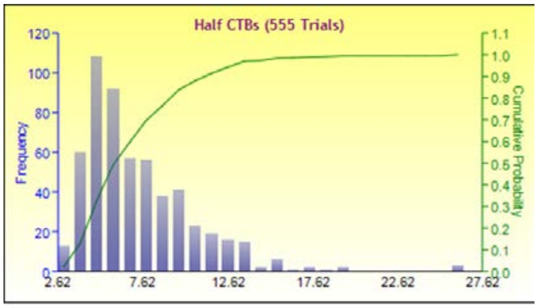
Monte Carlo methodologies represent a broad range of algorithms with an ever growing range of applications including finance, mathematics, physics, chemistry, radiation analysis, fluid dynamics, scheduling, cost analysis, reliability analysis, and risk assessment to name a few. Modern Monte Carlo techniques can be traced to the Manhattan Project where Stanislaw Ulam and John Von Neumann investigated the behavior of neutron chain reactions and multiplication rates using the developing computing technology of the time (Eckhardt 1987). Electronic computing was in its infancy at the time of Ulam and Von Neumann but the ensuing explosion of computing power enabled desktop Monte Carlo analyses to be available for the masses.

Monte Carlo methods can be described as repeated random sampling of statistical input parameters based on user prescribed condition in form of a probability distribution, geometry, material properties defining representative probabilities that are then ultimately calculated into numerical value output.

Monte Carlo analyses/techniques encompass a wide array of methodologies. The specific methodology used for this thesis is commonly referred to as Monte Carlo simulation. Monte Carlo simulation models a system where the inputs of the various elements are represented by individual probability distributions from which the performance is then represented in the form of another probability distribution for the entirety of the system. Perhaps the most illustrative example of Monte Carlo simulation is reliability analysis. The reliability of individual components or sub-systems are input to model the performance of the larger system with the result being a probability distribution for the larger system. Numerous Monte Carlo simulation packages have been released over the years: @Risk, Crystal Ball, XLSim, and Real Options Valuation's Risk Simulator, among others. Risk Simulator was the software used for this effort.

C. ANALYSIS OF THE HISTORICAL DATA

The large and growing dataset of cargo bag mass is a natural candidate for predictive Monte Carlos simulation. To improve our understanding of the underlying data, we must first examine how the data is distributed. Figure 4 shows the histograms and cumulative distribution functions (CDF) for the historical data for the seven standard bag types.



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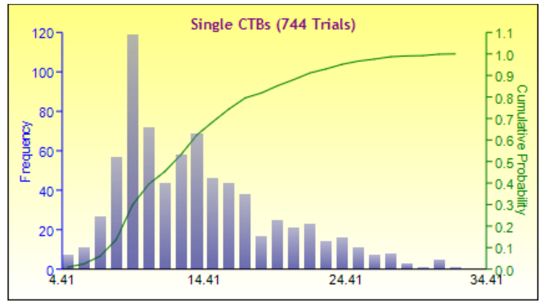

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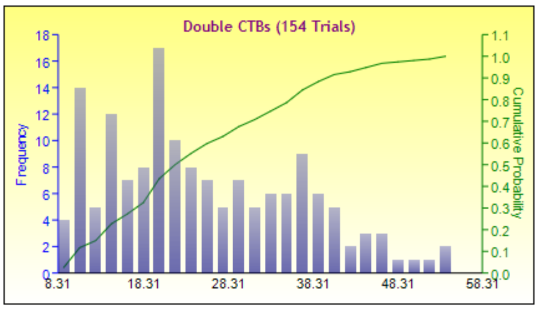

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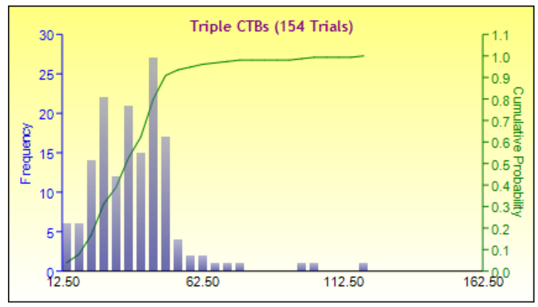

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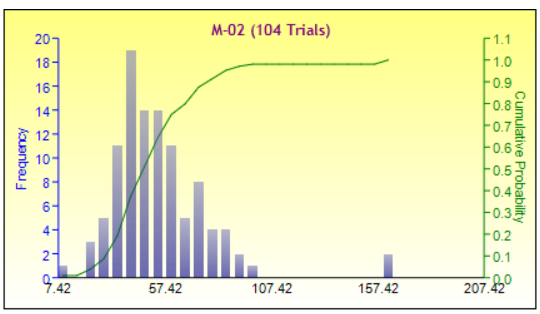

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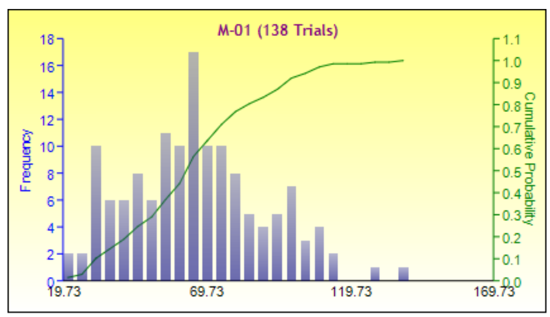

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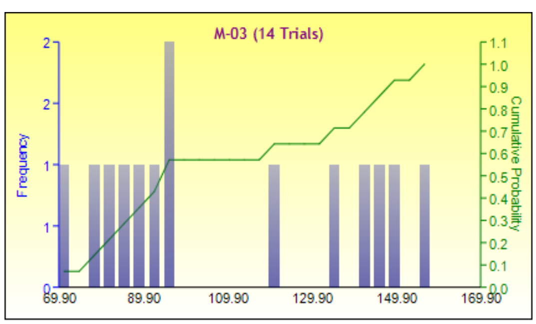

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Figure 4. Histograms and CDFs for Cargo Bags by Type

The single variable distribution fitting tool in Risk Simulator can be used to determine which, if any, of the available distributions fit the historical data. Table 6 presents the resulting best fit distributions along with comparisons of the actual and theoretical values for mean, standard deviation, skewness, and kurtosis.

Table 6. Best Fit Distributions by Bag Type

Bag Type	Data Points	Data Type	Best Fit Distribution	p-Value	Mean (kg)	Standard Deviation	Skewness	Kurtosis
Half CTB	555	Actual	--	--	6.87	3.31	1.78	5.61
		Theoretical	Lognormal-3	0.5507	6.93	3.49	1.97	7.58
Single CTB	744	Actual	--	--	13.34	5.45	0.90	0.33
		Theoretical	Lognormal-3	0.1263	13.12	5.63	1.50	4.23
Double CTB	154	Actual	--	--	24.52	11.31	0.51	-0.56
		Theoretical	Gumbel Maximum	0.9280	25.11	12.71	1.14	2.40
Triple CTB	154	Actual	--	--	36.05	15.64	1.76	6.91
		Theoretical	Gumbel Minimum	0.5579	33.90	14.43	-1.14	2.40
M-02	104	Actual	--	--	51.48	23.38	2.07	8.01
		Theoretical	Gumbel Maximum	0.9954	51.28	20.71	1.14	2.40
M-01	138	Actual	--	--	63.67	23.93	0.40	0.08
		Theoretical	Normal	0.9502	62.84	23.52	0.00	0.00
M-03	14	Actual	--	--	108.09	30.78	0.36	-1.58
		Theoretical	Lognormal	0.8777	110.38	44.34	1.27	3.00

Risk Simulator tests for best fit use a null hypothesis that the fitted distribution is the same population as the historical data comes from (Mun 2012). Any p-values greater than the critical alpha of 0.05 indicate that the best fit curve rejects the null hypothesis, and the best fit is a good one. Further, the higher the p-value, the better the best fit curve fit is (Mun undated). Table 6 shows that the

best fit curves are acceptable for all the bag types. The double CTB, M-02, and M-01 bag types all with p-values above 90% indicating very good curve fits. The Lognormal distribution produced a p-value of nearly 88% for M-03 bags on a limited data set, also indicating that the fit accounts for most of the variation. The type and frequency of the cargo flown in these bags, however, necessitates that they be handled as special cases in the manifesting process and are not fundamental to this research. Further discussion on M-03 bags and other special cargo types is presented later in this document. Good enough fitting distributions were found for Half, Single, and Triple CTBs, although the p-value for the Single CTB is low so only about 12% of the variation is accounted for by the best fit result.

Risk Simulator offers the ability to create custom distributions for datasets where good fits are not able to be found. This option provides a convenient solution for the Half, Single, and Triple CTB bag sizes. And while the best-fits identified in Table 3 would have been acceptable for the remaining bag types, custom distributions were also created for these.

D. CHAPTER SUMMARY

Thirteen years of ISS cargo resupply data encompassing 29 flights was collected and analyzed. The inherent risk of using a single number such as a calculated average to represent a variable input for predictive purposes was discussed. The development and proliferation of Monte Carlo simulation has the potential to provide a straight-forward and easily accessible a remedy for this. With custom probability distributions for the standard bag types, models can be built and executed using Monte Carlo simulations.

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IV. CONSTRUCTING AND RUNNING THE SIMULATION

The complex, time-consuming, and potentially costly process of accurately predicting cargo bag masses more than a year in advance is a potential candidate for improvement by using Monte Carlo simulation with a sufficient amount of relevant, historical data to support it. This chapter will detail the construction and execution of Monte Carlo simulations for two CRS flights, SpX-3 and Orb-2. Risk Simulator was used for this investigation, and like many of the Monte Carlo simulation packages, runs on a Microsoft Excel platform.

Setting up the simulations is the first step in a two-step process toward improving the initial bag-level bag mass estimates. The simulations will provide active histograms and distribution statistics for the individual bag sizes in the flight bag complement as well as for the overall total bag mass for the flight. The histograms and statistics will then be used in the second step of the process to actually build the bag-level manifest for the subject flights.

A. FLIGHT SPX-3

1. Building the Simulation

The first step in utilizing Risk Simulator to build the simulation is to define the bag complement of the spacecraft in an Excel spreadsheet. Individual cells were created for each bag with the bag type and count number to serve as an identifier. The adjacent cells are linked to the custom distributions created in Chapter II for each bag size using the Input Assumption in Risk Simulator. These cells will run individual simulations for each bag based on the corresponding distribution. Finally, a cell with the sum for all of the individual bag simulation cells reflected in Equation 1 was created. The initial bag complement for SpX-3 is shown in Table 7 and a representation of the as-constructed simulation spreadsheet is shown in Figure 5.

Table 7. SpX-3 Initial Bag Complement

Bag size	Number of bags
Half CTB	15
Single CTB	25
Double CTB	6
Triple CTB	0
M-02	4
M-01	6
M-03	0

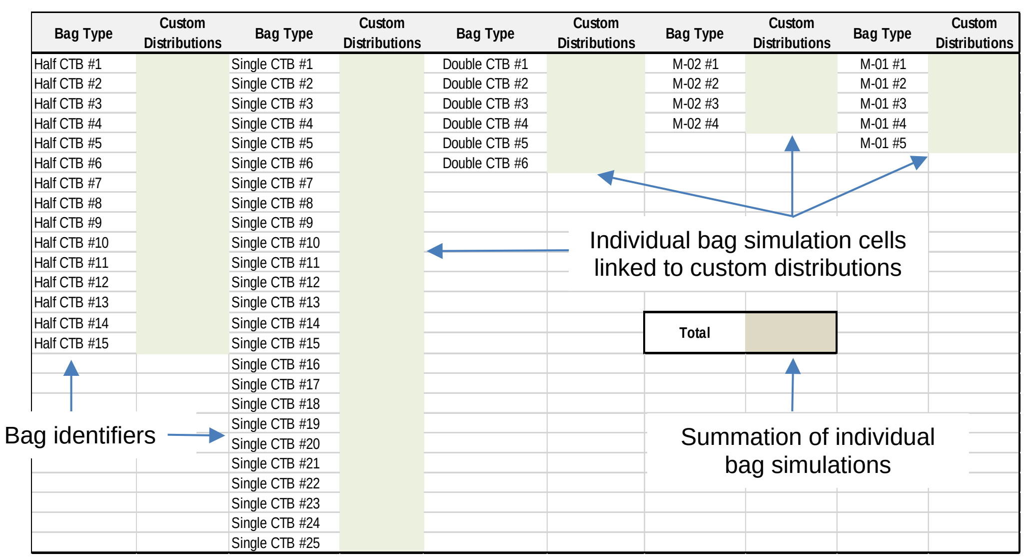

Figure 5. SpX-3 Simulation Spreadsheet

$$\text{Total} = m_{\text{half CTB \#1}} + m_{\text{half CTB \#2}} + m_{\text{half CTB \#3}} + m_{\text{half CTB \#4}} + m_{\text{half CTB \#5}} + m_{\text{half CTB \#6}} + m_{\text{half CTB \#7}} + m_{\text{half CTB \#8}} + m_{\text{half CTB \#9}} + m_{\text{half CTB \#10}} + m_{\text{half CTB \#11}} + m_{\text{half CTB \#12}} + m_{\text{half CTB \#13}} + m_{\text{half CTB \#14}} + m_{\text{half CTB \#15}} + m_{\text{single CTB \#1}} + m_{\text{single CTB \#2}} + m_{\text{single CTB \#3}} + m_{\text{single CTB \#4}} + m_{\text{single CTB \#5}} + m_{\text{single CTB \#6}} + m_{\text{single CTB \#7}} + m_{\text{single CTB \#8}} + m_{\text{single CTB \#9}} + m_{\text{single CTB \#10}} + m_{\text{single CTB \#11}} + m_{\text{single CTB \#12}} + m_{\text{single CTB \#13}} + m_{\text{single CTB \#14}} + m_{\text{single CTB \#15}} + m_{\text{single CTB \#16}} + m_{\text{single CTB \#17}} + m_{\text{single CTB \#18}} + m_{\text{single CTB \#19}} + m_{\text{single CTB \#20}} + m_{\text{single CTB \#21}} + m_{\text{single CTB \#22}} + m_{\text{single CTB \#23}} + m_{\text{single CTB \#24}} + m_{\text{single CTB \#25}} + m_{\text{double CTB \#1}} + m_{\text{double CTB \#2}} + m_{\text{double CTB \#3}} + m_{\text{double CTB \#4}} + m_{\text{double CTB \#5}} + m_{\text{double CTB \#6}} + m_{\text{M-02 \#1}} + m_{\text{M-02 \#2}} + m_{\text{M-02 \#3}} + m_{\text{M-02 \#4}} + m_{\text{M-01 \#1}} + m_{\text{M-01 \#2}} + m_{\text{M-01 \#3}} + m_{\text{M-01 \#4}} + m_{\text{M-01 \#5}} + m_{\text{M-01 \#6}} \quad \text{[Eq 1]}$$

The output, or forecast, from the simulation is defined to provide the simulation results with the desired information. One forecast cell was defined for each bag type as well one for the summation of the individual bags. The output for the bag types essentially replicated the respective custom bag distributions and will become useful in the next section. The summation cell represented the probability distribution for the total mass of the bagged cargo. The simulation is now ready to run.

2. Running the Simulation

This is a rather simple simulation relative to the available computing power of even the most modest current personal computers and thus simulation was set to 100,000 trials. While this was likely overkill for this application, the impact on run time to convergence was negligible.

The output of the simulation is six forecast charts that include active histograms and tabs for statistics, preferences, options, and controls, for each bag type in the complement and one for the overall total mass. The active histograms allow the user to select specific percentile ranges corresponding to a level-of-confidence percentage using either right-tail, left-tail, or two-tail selection

margins. The histogram for the total mass for the SpX-3 simulation is presented in Figure 6. The simulation results for the individual bag forecast cells are contained in the appendix.

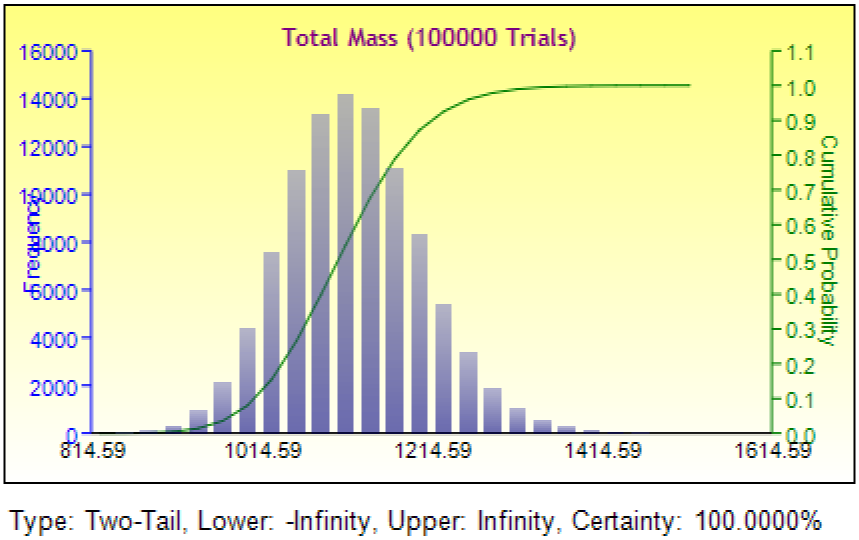

Figure 6. Total Cargo Mass Histogram for SpX-3

The statistics tab is the second item of particular utility and provides the statistical data corresponding forecast including number of trials, mean, median, standard deviation, variance, coefficient of variation, maximum and minimum values, range of values, skewness, kurtosis, 25th and 75th percentiles, and percentage error precision at 95% confidence. This data is presented in Table 8.

Table 8. Total Mass Statistical Data for SpX-3

Number of Trials	100,000
Mean	1,108.45
Median	1,105.32
Standard Deviation	81.65
Variance	6,666.09
Coefficient of Variation	0.0737
Maximum	1,517.98
Minimum	795.81
Range	722.17
Skewness	0.2692
Kurtosis	0.2372
25th Percentile	1,052.2200
75th Percentile	1,160.6500
Percentage Error Precision at 95% Confidence	0.0457%

Further insight into the resulting total mass distribution can be gained from examining its first four moments. The first moment looks at the mean, median and mode to measure the center of the distribution. For the total mass simulation distribution the mean and median are nearly identical at 1,108 kg and 1,105 kg, respectively, and the mode was not calculated.

The second moment measures the variance, or spread, of the distribution. Variance is often considered a measurement of risk, that is, it determines the probability that the variable (outcome of total mass in this case) will land in different regions of the distribution. A more familiar statistic denoting similar likelihood is standard deviation, which is simply the absolute value of the square root of the variance. The standard deviation for this distribution is 81.65 kg.

The asymmetry or “lean” of a distribution to one side or the other is referred to as the skewness and is the third moment. The convention is a positive, or right, skew has the longer tail of the distribution on the right, and a negative, or left, skew has the longer tail on the left. Skewness can be a useful tool for selecting options, such as which project has the greater probability for success. The SpX-3 total mass histogram shows negligible asymmetry and is supported by the low skewness value of 0.27.

The fourth, and final moment considered here is kurtosis. Kurtosis is a measure of how peaked the distribution is. Higher kurtosis values are indicative of a lower peak and more weight of the distribution carried at the tails. As kurtosis increases the distributions approach uniformity, meaning the outcomes on either side are more likely. The kurtosis for the total mass of 0.2372 shows very little “excess” kurtosis in this distribution.

B. FLIGHT ORB-2

1. Building the Simulation

The construction and execution steps were repeated for Orbital’s Cygnus spacecraft. It is almost the direct opposite of SpaceX’s Dragon, as it has very few of the smaller bags and many more M-02s in its complement, shown here in Table 9.

Table 9. Orb-2 Initial Bag Complement

Bag size	Number of bags
Half CTB	0
Single CTB	4
Double CTB	2
Triple CTB	3
M-02	18
M-01	2
M-03	0

This simulation was built using the projected Orb-2 bag complement, again linking the input cells to the custom bag distributions for that bag type. Figure 7 shows a representation of the Orb-2 simulation spreadsheet.

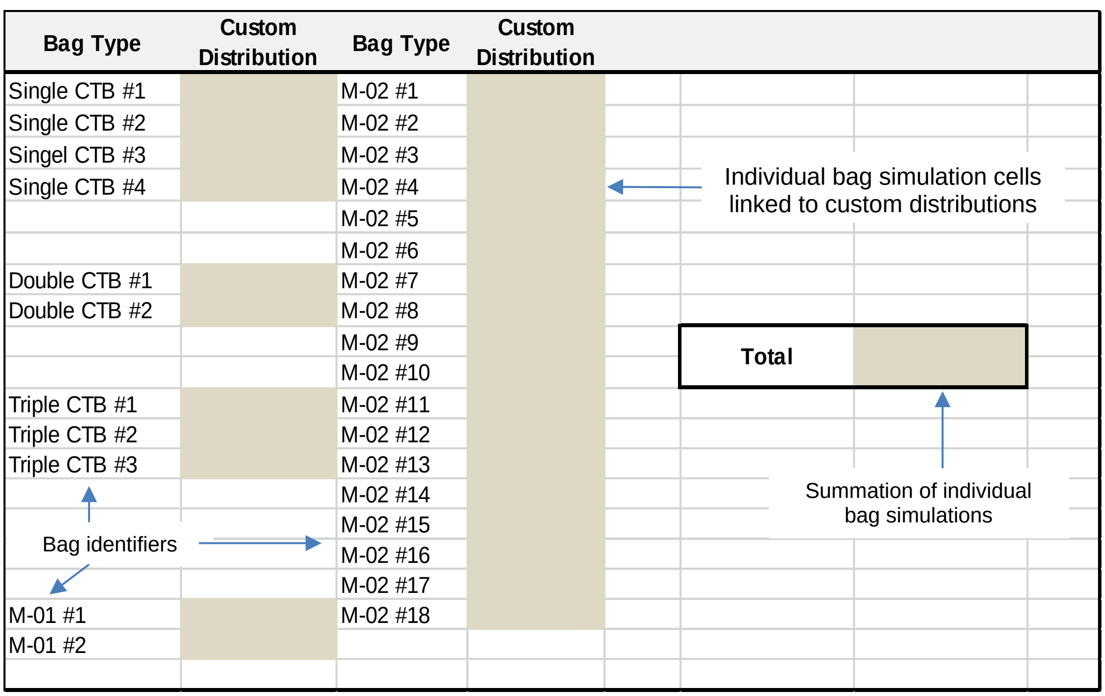

Figure 7. Orb-2 Simulation Spreadsheet

As is the case with the SpX-3 simulation, there are also six desired forecast, or output, cells. There is one forecast cell for each bag type, this time with Triple CTBs in lieu of Half CTBs, and one for the summation of all of the individual bag simulations, shown in Equation 2.

$$\text{Total} = m_{\text{single CTB \#1}} + m_{\text{single CTB \#2}} + m_{\text{single CTB \#3}} + m_{\text{single CTB \#4}} + m_{\text{double CTB \#1}} + m_{\text{double CTB \#2}} + m_{\text{triple CTB \#1}} + m_{\text{triple CTB \#2}} + m_{\text{triple CTB \#3}} + m_{\text{M-02 \#1}} + m_{\text{M-02 \#2}} + m_{\text{M-02 \#3}} + m_{\text{M-02 \#4}} + m_{\text{M-02 \#5}} + m_{\text{M-02 \#6}} + m_{\text{M-02 \#7}} + m_{\text{M-02 \#8}} + m_{\text{M-02 \#9}} + m_{\text{M-02 \#10}} + m_{\text{M-02 \#11}} + m_{\text{M-02 \#1}} + m_{\text{M-02 \#12}} + m_{\text{M-02 \#13}} + m_{\text{M-02 \#14}} + m_{\text{M-01 \#15}} + m_{\text{M-02 \#16}} + m_{\text{M-02 \#17}} + m_{\text{M-02 \#18}} \quad \text{[Eq 2]}$$

2. Running the Simulation

Again, the simulation was set for 100,000 trials and was completed within a few minutes. The histogram and statistics for the Orb-2 Total Mass simulation are presented in Figure 8 and Table 10, respectively.

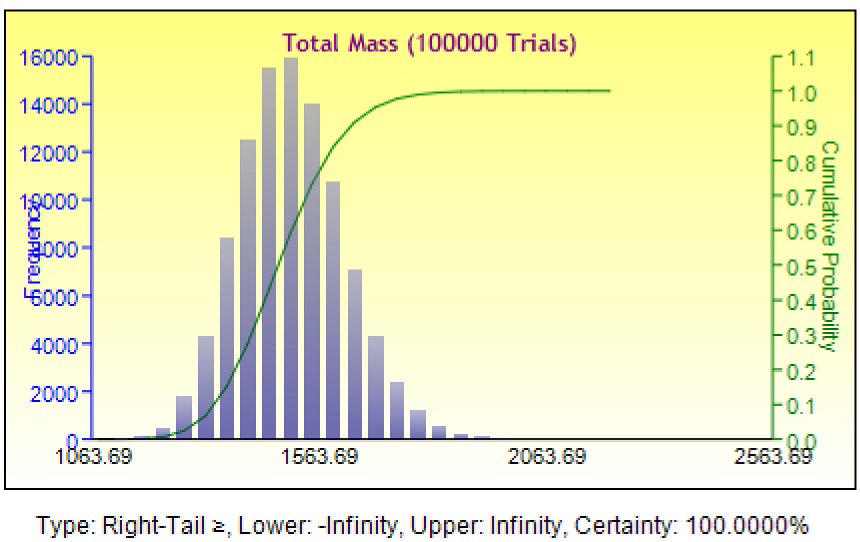

Figure 8. Total Cargo Mass Histogram for Orb-2

Table 10. Total Mass Statistical Data for Orb-2

Number of Trials	100,000
Mean	1,480.99
Median	1,474.71
Standard Deviation	117.52
Variance	13,810.3
Coefficient of Variation	0.0794
Maximum	2,205.40
Minimum	1,033.21
Range	1,172.19
Skewness	0.3251
Kurtosis	0.2117
25th Percentile	1,399.07
75th Percentile	1,555.96
Percentage Error Precision at 95% Confidence	0.0492%

Examining the four moments for this simulation both the mean and median are higher, as expected, attributable to Orbital's volumetric capability. This simulation has slightly more positive skew compared to SpX-3 while the kurtosis is negligibly less.

Both of the vehicle-specific Monte Carlo simulations successfully converged. The desired outputs in the form of the active histograms and corresponding statistics were generated. While no specific findings or interpretations can be made from these results, they are suitable for use in the second step of this two-step process presented in Chapter V.

C. CHAPTER SUMMARY

Vehicle-specific Monte Carlo simulations for the SpX-3 and Orb-2 resupply flights have been constructed and executed and have successfully converged. Each of these simulations generated six active histograms, one for each bag size in the complement and one for the total mass, and the related statistics for the distribution. These results are applied to build a mission-specific bag level manifest with the goal of improving the early bag mass property predictions over the current methods.

V. TESTING THE SIMULATIONS

The active histograms and supporting statistics output from running the simulations can now be applied in an attempt to build bag-level manifest estimates for the early deliverables that are more representative of what the actual, as-flown manifest might be.

SpX-3 and Orb-2 share the uniqueness of being the first flights for their respective companies to launch and return (or dispose) with a full cargo complement. These flights were not chosen because of this shared characteristic, rather, they were the next flights in flow at the beginning of this study. Being the first, fully manifested flight presented the unique challenge of having limited history to serve as a starting point for improving the initial bag-level manifests. Determining the distributions of the various bag types was admittedly more art than science, based on judgment and experience accumulated over years of supporting human spaceflight and the ISS program. As a result, this approach hopes to serve as a proof-of-concept that can be refined as the number of commercial resupply flights accrue.

A. BUILDING THE BAG-LEVEL MANIFEST ESTIMATES

1. Flight SpX-3

Building the bag-level manifest begins with the SpX-3 bag complement, presented previously in Table 7. Starting with the Half CTBs and the associated histograms and statistics output from the simulation, the individual bag masses can be estimated. SpX-3 was the first fully manifested cargo flight and combined with the lack of acceptable distributional fits for the various bag types, the rule of "68-95-99.7" for normal distributions was used a loose guideline for predicting the bag masses; that is, for all normal distributions 68% of all observations will fall between the mean (μ) ± one standard deviation (σ), 95% will fall between $\mu \pm 2\sigma$, and 99.7% will fall between $\mu \pm 3\sigma$. From Table 6, μ for the Half CTBs was 6.88 kg with σ of 3.32 kg. Sixty eight percent of 15 bags is approximately 11. These

11 bags were estimated between 3.55 kg (μ - σ) and 10.2 kg (μ + σ). Six of these 11 were estimated at mean of 6.88 kg. Using the active histogram, two were chosen at 4.92 kg corresponding to the 33^{rd} percentile, and three at 8.59 kg corresponding to the 75^{th} percentile. Expanding out on the low side, two Half CTBs were estimated at 3.27 kg and 3.74 kg, the 5^{th} and 10^{th} percentiles, respectively. Closing out the Half CTBs, one bag each was estimated at 11.3 (90^{th} percentile) and 12.9 kg (95^{th} percentile) on the high side.

The same "68-95-99.7" guideline was applied again in estimating the masses of 25 Single CTBs in the complement. For the 68% percent range, ten Singles CTBs were estimated at the mean of 13.4 kg, three at 9.63 kg (μ - σ), and three at 16.4 kg (μ + σ). These correspond to Single bag masses at the 33^{rd}, 58^{th}, and 75^{th} percentiles. The Single bag mass predictions were rounded out on the low side with two bags at 6.6 kg and two bags at 7.7 kg, the 5^{th} and 10^{th} percentiles, respectively. On the high side, three bags were predicted at 21.7 kg (90^{th} percentile) and two at 23.9 kg (95^{th} percentile).

Dragon's pressurized volume's shape and design limits the number of larger bags that can be accommodated. Six Double CTBs, four M-02s, and six M-01s are part of the complement. The direct application of the Monte Carlo simulation is less valuable when only a few bags of each type are available. The approach taken for each of these bag sizes was to predict one bag at the 33^{rd} percentile, one at the 75^{th} percentile, with the remaining bags were predicted at the mean.

Table 11 contains the complete preflight estimated bag-level manifest using the Monte Carlo simulation as described above. The table also includes the manifest produced from the uniform average bag mass estimated manifest. The average bag method used the calculated mean for each bag size rather than the masses shown in Table 3 to isolate any improvement realized by using the Monte Carlo method.

Table 11. SpX-3 Preflight Bag-Level Manifest Predictions

Bag ID	Average Mass Method kg	Monte Carlo Method kg	Percentile
Half CTB 1	6.87	3.27	5
Half CTB 2	6.87	3.74	10
Half CTB 3	6.87	4.92	33
Half CTB 4	6.87	4.92	33
Half CTB 5	6.87	6.87	60
Half CTB 6	6.87	6.87	60
Half CTB 7	6.87	6.87	60
Half CTB 8	6.87	6.87	60
Half CTB 9	6.87	6.87	60
Half CTB 10	6.87	6.87	60
Half CTB 11	6.87	8.59	75
Half CTB 12	6.87	8.59	75
Half CTB 13	6.87	8.59	75
Half CTB 14	6.87	11.3	90
Half CTB 15	6.87	12.9	95
Single CTB 1	13.4	6.6	5
Single CTB 2	13.4	6.6	5
Single CTB 3	13.4	7.7	10
Single CTB 4	13.4	7.7	10
Single CTB 5	13.4	9.63	33
Single CTB 6	13.4	9.63	33
Single CTB 7	13.4	9.63	33
Single CTB 8	13.4	13.4	58
Single CTB 9	13.4	13.4	58
Single CTB 10	13.4	13.4	58
Single CTB 11	13.4	13.4	58
Single CTB 12	13.4	13.4	58
Single CTB 13	13.4	13.4	58
Single CTB 14	13.4	13.4	58
Single CTB 15	13.4	13.4	58
Single CTB 16	13.4	13.4	58
Single CTB 17	13.4	13.4	58
Single CTB 18	13.4	16.4	75
Single CTB 19	13.4	16.4	75
Single CTB 20	13.4	16.4	75
Single CTB 21	13.4	21.7	90
Single CTB 22	13.4	21.7	90
Single CTB 23	13.4	21.7	90
Single CTB 24	13.4	24.5	95
Single CTB 25	13.4	24.5	95
Double CTB 1	24.5	18.6	33
Double CTB 2	24.5	24.5	57
Double CTB 3	24.5	24.5	57
Double CTB 4	24.5	24.5	57
Double CTB 5	24.5	24.5	57
Double CTB 6	24.5	33.6	75
M-01 1	63.7	53.1	33
M-01 2	63.7	63.7	55
M-01 3	63.7	63.7	55
M-01 4	63.7	63.7	55
M-01 5	63.7	63.7	55
M-01 6	63.7	76.8	75
M-02 1	51.5	40	33
M-02 2	51.5	51.5	55
M-02 3	51.5	51.5	55
M-02 4	51.5	61.5	75
TOTALS	**1173.3**	**1202.2**	

SpX-3 launched in April of 2014, over 13 months after SpX-2. This lengthy delay was the result of SpaceX's transition from the Falcon 9 launch vehicle to the new Falcon 9 1.1 launch vehicle. SpX-3 also represented the first flight of a

redesigned Dragon pressurized volume. As a result, the initial bag complement submitted to SpaceX as presented above had to be updated to reflect the new cargo configuration and capability and the pre-flight predictions were updated. The new design was, in part, in response to NASA's request for additional powered payload and passive thermally-conditioned bag locations, which are not included in the thesis. The number of Single CTBs was reduced from 25 to 17, the number of Double CTBs was increased from six to 10, and the number of M-01s was reduced from six to five.

Both the average-mass and the Monte Carlo predictions were updated to reflect the new capability. Eight Single CTBs were deleted from the average-mass method prediction and replace by four Double CTBs. To maintain consistency in the prediction, the newly added Double CTBs were estimated at 26.7 kg, the sum to two average Single CTBs, instead of the 24.5 kg average for Double CTBs. For the Monte Carlo method, four Single CTBs at the average mass (13.4 kg) plus one each at 9.63 kg, 16.4 kg, 21.7 kg, and 23.9 kg were deleted and replaced with four Double CTBs as shown in Table 12.

Table 12. Bag Replacements for SpX-3 Dragon Configuration

New bags	Mass (kg)	Double CTB Percentile	Replaces
Double CTB #2	23.0	52nd	Single CTBs #7 & #14 (9.63 kg + 13.4 kg)
Double CTB #8	29.8	68th	Single CTBs #15 & #20 (13.4 kg + 16.4 kg)
Double CTB #9	35.1	78th	Single CTBs #16 & #23 (13.4 kg + 21.7 kg)
Double CTB #10	37.3	85th	Single CTBs #17 & #25 (13.4 kg + 23.9 kg)

The complete, updated bag-level manifest with updated bag numbering is presented in Table 13. This manifest will be used for remainder of the SpX-3 portion of this study.

Table 13. Updated SpX-3 Preflight Bag-Level Manifest Predictions

Bag ID	Average Mass Method kg	Monte Carlo Method kg	Percentile
Half CTB 1	6.87	3.27	5
Half CTB 2	6.87	3.74	10
Half CTB 3	6.87	4.92	33
Half CTB 4	6.87	4.92	33
Half CTB 5	6.87	6.87	60
Half CTB 6	6.87	6.87	60
Half CTB 7	6.87	6.87	60
Half CTB 8	6.87	6.87	60
Half CTB 9	6.87	6.87	60
Half CTB 10	6.87	6.87	60
Half CTB 11	6.87	8.59	75
Half CTB 12	6.87	8.59	75
Half CTB 13	6.87	8.59	75
Half CTB 14	6.87	11.3	90
Half CTB 15	6.87	12.9	95
Single CTB 1	13.4	6.6	5
Single CTB 2	13.4	6.6	5
Single CTB 3	13.4	7.7	10
Single CTB 4	13.4	7.7	10
Single CTB 5	13.4	9.63	33
Single CTB 6	13.4	9.63	33
Single CTB 7	13.4	13.4	58
Single CTB 8	13.4	13.4	58
Single CTB 9	13.4	13.4	58
Single CTB 10	13.4	13.4	58
Single CTB 11	13.4	13.4	58
Single CTB 12	13.4	13.4	58
Single CTB 13	13.4	16.4	75
Single CTB 14	13.4	16.4	75
Single CTB 15	13.4	21.7	90
Single CTB 16	13.4	21.7	90
Single CTB 17	13.4	24.5	95
Double CTB 1	24.5	18.6	33
Double CTB 2	24.5	23.0	52
Double CTB 3	24.5	24.5	57
Double CTB 4	24.5	24.5	57
Double CTB 5	24.5	24.5	57
Double CTB 6	24.5	24.5	57
Double CTB 7	26.7	29.8	68
Double CTB 8	26.7	33.6	75
Double CTB 9	26.7	35.1	78
Double CTB 10	26.7	37.3	85
M-01 1	63.7	53.1	33
M-01 2	63.7	63.7	55
M-01 3	63.7	63.7	55
M-01 4	63.7	63.7	55
M-01 5	63.7	76.8	75
M-02 1	51.5	40	33
M-02 2	51.5	51.5	55
M-02 3	51.5	51.5	55
M-02 4	51.5	61.5	75
TOTALS	**1109.15**	**1137.9**	

2. Flight Orb-2

Similar to SpX-3, Orb-2 was the first fully manifested flight of the Cygnus spacecraft with no preceding data. The Cygnus spacecraft differed from Dragon

in that its bag complement is heavily skewed toward larger cargo bags, specifically M-02s. Recalling the bag complement presented in Table 9, there are only four Single CTBs, two Double CTBs, and three Triple CTBs. For the Single CTBs, two are predicted at the mean of 13.4 kg and one each at 9.6 kg (33^{rd} percentile) and 16.4 kg (75^{th} percentile). The two Double CTBs and three Triple CTBs are predicted at their respective means of 26.4 kg and 39.2 kg. Orb-2, only accommodated two M-01 bags and those are also predicted at their mean of 66.1 kg.

There are also two M-03 bags in the bag complement for Orb-2 M-03s were relatively rare during the 13-year period encompassed by the historical data with only 14 occurrences. The mean of the historical data is 108 kg, however, judgment based on experience and current trending suggests that M-03s flown now will nearly always be heavier. For the sake of this study these predictions were held at 108 kg for consistency.

The potential value of using the Monte Carlo simulation results is better realized for larger populations of bags and that is the M-02 size for Cygnus with 18 bags in the complement. Again, lacking any previous full manifest, the loose application of the “68-95-99.7” rule was used as an initial guideline. Starting with the middle 68%, seven M-02s are predicted at the mean of 51.5 kg, two at 33^{rd} percentile of 40 kg, and three at the 66^{th} percentile 0f 54.3 kg. The lighter M-02s were predicted at 24.3 kg, the 5^{th} percentile, and 29.9, the 10^{th} percentile. Recent history indicates that M-02s are being more densely packed so the heavier bags were represented with two at 61.5 kgs, the 75^{th} percentile, one at 75.1 kg, the 90^{th} percentile, and one at 85.7 kg, the 95^{th} percentile. The preflight bag-level manifests for Orb-2 derived using the Monte Carlo method describe above, and the average-mass method are shown in Table 14.

Table 14. Orb-2 Preflight Bag-level Manifest Predictions

Bag ID	Average Mass Method kg	Monte Carlo Method kg	Percentile
Single CTB 1	13.4	9.6	33
Single CTB 2	13.4	13.4	58
Singel CTB 3	13.4	13.4	58
Single CTB 4	13.4	16.4	75
Double CTB 1	24.5	24.5	57
Double CTB 2	24.5	24.5	57
Triple CTB 1	36.1	36.1	53
Triple CTB 2	36.1	36.1	53
Triple CTB 3	36.1	36.1	53
M-01 1	63.7	63.7	55
M-01 2	63.7	63.7	55
M-02 1	51.5	24.3	5
M-02 2	51.5	29.9	10
M-02 3	51.5	40.0	33
M-02 4	51.5	40.0	33
M-02 5	51.5	51.5	55
M-02 6	51.5	51.5	55
M-02 7	51.5	51.5	55
M-02 8	51.5	51.5	55
M-02 9	51.5	51.5	55
M-02 10	51.5	51.5	55
M-02 11	51.5	51.5	55
M-02 12	51.5	54.3	66
M-02 13	51.5	54.3	66
M-02 14	51.5	54.3	66
M-02 15	51.5	61.5	75
M-02 16	51.5	61.5	75
M-02 17	51.5	75.1	90
M-02 18	51.5	85.7	95
M-03 1	108.0	108.0	58
M-03 2	108.0	108.0	58
TOTALS	**1481.3**	**1494.9**	

B. RESULTS

The bag-level manifest predictions are now ready to be compared with the as-flown manifests for the two flights subject in this study.

1. Flight SpX-3

The average-mass and Monte Carlo simulation based pre-flight manifest predictions are presented in Table 15 with the as-flown bag masses. The left-most columns repeat the updated preflight predictions in Table 13. Working to

the right, the next column contains the masses as-flown bags, as weighed by CMC at the conclusion of packing. Comparison of the predictions to the as-flown manifest are presented as both the difference between the predicted mass and the as-flown mass for each bag in kg, and then percentage of difference. The difference calculated is the predicted mass less the as-flown mass, thus the sign convention is positive if the prediction method over-predicted the mass for the bag, or negative if the prediction under-predicted the mass. This sign convention is carried through to the percentage difference. The final column is titled percentage improvement and represents the absolute value of the percentage difference from the average-mass method less the absolute value of the Monte Carlo percentage difference. When this value is positive, the Monte Carlo method prediction was closer to the as-flown mass than the average-mass method; when negative, the Monte Carlo method prediction was worse. The absolute value of the percentages were used because over-predicting or under-predicting the masses of individual bags at this point in the manifest process less important than reducing the magnitude of the difference between the predicted mass and the mass of the bag delivered for flight.

Using Half CTB 1 as an example, the average-mass method predicted this bag at the historical mean of 6.87 kg. The lightest as-flown Half CTB on this flight was 4.08 kg, for a difference of 2.79 kg, over-predicting the mass by 41%. The same bag using the Monte Carlo method was predicted to be 3.27 kg (the 5th percentile). The Monte Carlo method under-predicted the mass by 0.81 kg, shown as -0.81 in the table, and -25%. Subtracting the absolute values of the percentages, the Monte Carlo method improved the pre-flight prediction of the absolute mass by 16%.

Table 15. SpX-3 Preflight and As-Flown Manifest Comparisons

Bag ID	Average Mass Method kg	Monte Carlo Method kg	Percentile %	Actual As-Flown Mass kg	Average Mass Method Differential kg	Average Mass Method Percentage Difference %	Monte Carlo Method Differential kg	Monte Carlo Method Percentage Difference %	Percent Improvement %
Half CTB 1	6.87	3.27	5	4.08	2.79	**41%**	-0.81	**-25%**	16%
Half CTB 2	6.87	3.74	10	4.23	2.64	**38%**	-0.49	**-13%**	25%
Half CTB 3	6.87	4.92	33	4.27	2.60	**38%**	0.65	**13%**	25%
Half CTB 4	6.87	4.92	33	4.49	2.38	**35%**	0.43	**9%**	26%
Half CTB 5	6.87	6.87	60	5.49	1.38	**20%**	1.38	**20%**	0%
Half CTB 6	6.87	6.87	60	5.62	1.25	**18%**	1.25	**18%**	0%
Half CTB 7	6.87	6.87	60	6.29	0.58	**8%**	0.58	**8%**	0%
Half CTB 8	6.87	6.87	60	8.47	-1.60	**-23%**	-1.60	**-23%**	0%
Half CTB 9	6.87	6.87	60	8.91	-2.04	**-30%**	-2.04	**-30%**	0%
Half CTB 10	6.87	6.87	60	9.20	-2.33	**-34%**	-2.33	**-34%**	0%
Half CTB 11	6.87	8.59	75	9.44	-2.57	**-37%**	-0.85	**-10%**	28%
Half CTB 12	6.87	8.59	75	10.02	-3.15	**-46%**	-1.43	**-17%**	29%
Half CTB 13	6.87	8.59	75	10.06	-3.19	**-46%**	-1.47	**-17%**	29%
Half CTB 14	6.87	11.3	90	10.17	-3.30	**-48%**	1.13	**10%**	38%
Half CTB 15	6.87	12.9	95	10.18	-3.31	**-48%**	2.72	**21%**	27%
Single CTB 1	13.4	6.6	5	4.67	8.73	**65%**	1.93	**29%**	36%
Single CTB 2	13.4	6.6	5	5.53	7.87	**59%**	1.07	**16%**	43%
Single CTB 3	13.4	7.7	10	7.38	6.02	**45%**	0.32	**4%**	41%
Single CTB 4	13.4	7.7	10	7.92	5.48	**41%**	-0.22	**-3%**	38%
Single CTB 5	13.4	9.63	33	8.00	5.40	**40%**	1.63	**17%**	23%
Single CTB 6	13.4	9.63	33	8.16	5.24	**39%**	1.47	**15%**	24%
Single CTB 8	13.4	13.4	58	9.92	3.48	**26%**	3.48	**26%**	0%
Single CTB 9	13.4	13.4	58	11.61	1.79	**13%**	1.79	**13%**	0%
Single CTB 10	13.4	13.4	58	12.32	1.08	**8%**	1.08	**8%**	0%
Single CTB 11	13.4	13.4	58	13.38	0.02	**0%**	0.02	**0%**	0%
Single CTB 12	13.4	13.4	58	14.07	-0.67	**-5%**	-0.67	**-5%**	0%
Single CTB 13	13.4	13.4	58	16.98	-3.58	**-27%**	-3.58	**-27%**	0%
Single CTB 18	13.4	16.4	75	20.99	-7.59	**-57%**	-4.59	**-28%**	29%
Single CTB 19	13.4	16.4	75	21.58	-8.18	**-61%**	-5.18	**-32%**	29%
Single CTB 21	13.4	21.7	90	21.64	-8.24	**-61%**	0.06	**0%**	61%
Single CTB 22	13.4	21.7	90	22.36	-8.96	**-67%**	-0.66	**-3%**	64%
Single CTB 24	13.4	23.9	95	22.38	-8.98	**-67%**	1.52	**6%**	61%
Double CTB 1	24.5	18.6	33	18.49	6.01	**25%**	0.11	**1%**	24%
Double CTB 2	24.5	23	52	19.15	6.85	**22%**	3.85	**17%**	5%
Double CTB 3	24.5	24.5	57	24.05	0.45	**2%**	0.45	**2%**	0%
Double CTB 4	24.5	24.5	57	27.60	-0.90	**-13%**	-3.10	**-13%**	0%
Double CTB 5	24.5	24.5	57	33.38	-6.68	**-36%**	-8.88	**-36%**	0%
Double CTB 6	24.5	24.5	57	34.09	-9.59	**-39%**	-9.59	**-39%**	0%
Double CTB 7	26.7	29.8	68	35.97	-9.27	**-35%**	-6.17	**-21%**	14%
Double CTB 8	26.7	33.6	75	36.06	-9.36	**-35%**	1.24	**-7%**	28%
Double CTB 9	26.7	35.1	78	41.68	-14.98	**-56%**	-6.58	**-19%**	37%
Double CTB 10	26.7	37.3	85	43.31	-16.61	**-62%**	-6.01	**-16%**	46%
M-01 1	63.7	53.1	33	81.40	-17.70	**-28%**	-28.30	**-53%**	-26%
M-01 2	63.7	63.7	57	87.79	-24.09	**-38%**	-24.09	**-38%**	0%
M-01 3									
M-01 4									
M-01 5	63.7	76.8	75	107.29	-43.59	**-68%**	-30.49	**-40%**	29%
M-02 1	51.5	40	33	49.13	2.37	**5%**	-9.13	**-23%**	-18%
M-02 2	51.5	51.5	55	54.49	-2.99	**-6%**	-2.99	**6%**	0%
M-02 3									
M-02 4	51.5	61.5	75	54.81	-3.31	**-6%**	6.69	**11%**	-4%
M-03 1	115.2	115.2	--	131.88	-16.68	**-14%**	-16.68	**-14%**	0%
Clam shell (M-01)	63.7	63.7	--	138.33	-72.33	**-117%**	-72.23	**-117%**	0%
TOTALS	**1109.2**	**1137.3**		**1358.71**		**-12%**		**-9%**	**16.5%**

There are two items of note relative to the bag complement for SpX-3. First, recalling that the sizes of the bags are multiples of one another, it is not uncommon for bags of different sizes to be swapped over the course of launch

campaign depending on the desired cargo and the spacecraft's design. This scenario happened for SpX-3 where an M-03 was needed to accommodate a large piece of hardware and was flown in lieu of one M-01 and M-02. In Table 15, this is reflected as the deletion of M-01 4 and M-02 3 and the addition of M-03 1. For the predictive elements of this study, the displaced M-01 and M-02 were predicted at the averages and the new M-03 was predicted to be at the sum of these rather than at the historical average for M-03s. Since this prediction was the same for both the average-mass and Monte Carlo methods, it had no bearing on the results relative to the comparison of the predictive methods.

The second item of note is that a foam clamshell was required to launch a heavier cargo item and was added in place of M-01 3. This is an infrequent but not a singular scenario. There exist a select number of cargo items that require special accommodations for protection from launch environment and/or are slightly outside of the dimensions that can be accommodated in a bag. This particular item was significantly heavier than the average M-01 that was predicted. Instances where clamshells or other one-off situations with drastic weight implications such as this one are typically known well in advance or communicated to the CRS provider as soon as they are known. That was indeed the case here, and it was more readily accommodated with the extended time before the SpX-3 launch. This change would have also been captured in an intermediate delivery but not necessarily in the initial and final bag-level manifests presented in this study. Again, there is no bearing on the outcome of this study because the predicted mass of that singular item was handled the same for both predictive methods.

Comparison of the results show that using a Monte Carlo derived method increased the accuracy of the predictions over 16% for all bag sizes. Examining the more plentiful bag sizes in the complement, Half, Single, and Double CTBs in the case of Dragon, show improvements of 16%, 25%, and 15%, respectively. These improvements are listed in Table 16.

Table 16. Average Improved Accuracy for SpX-3 Manifest by Bag Size

Bag size	Number of bags	Percent Improvement
Half CTB	15	16%
Single CTB	18	25%
Double CTB	10	15%

The results for these three bag sizes is better represented graphically. Figure 9 plots the average-mass and Monte Carlo method predictions against the as-flown masses. Although the absolute mass of the individual bags may not always agree, the profiles for the Monte Carlo derived distributions are more representative of an actual flight manifest. Dragon's limited large bag capability and the approach selected to predict the majority of these bag at historical averages minimized their effect on this study.

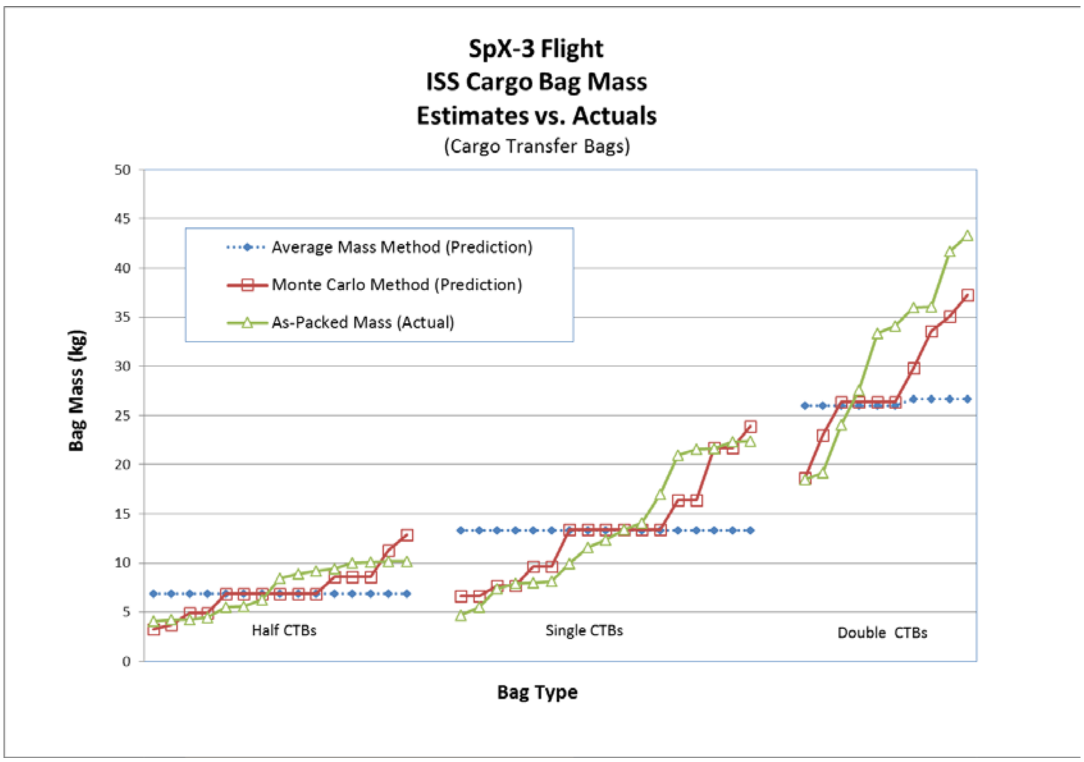

Figure 9. SpX-3 Preflight Predictions versus As-Flown Bag Masses

2. Flight Orb-2

The results for the Orb-2 manifest are presented in Table 17 in the same format as for SpX-3. Contrary to SpaceX's Dragon, Orbital's Cygnus spacecraft is geared to accommodate more of the larger bag sizes, and primarily M-02s. Few other CTB and M bag sizes are included so any potential overall improvement is driven by the M-02s. To this point, the overall average improvement was slightly over 3% mirroring the 3% average improvement for the M-02s. Reviewing the Monte Carlo predictions and the as-flown date it is clear that the "68-95-99.7" guideline based on the historical did not necessarily reflect the distribution of the as-flown M-02s. It is noteworthy that the low end of mass range the chosen distribution based on the Monte Carlo method under-predicted the mass by an average of 13 kg, or 40%.

Table 17. Orb-2 Preflight and As-Flown Manifest Comparisons

Bag ID	Average Mass Method kg	Monte Carlo Method kg	Percentile	Actual As-Flown Mass kg	Average Mass Method Differential kg	Average Mass Method Percentage Difference %	Monte Carlo Method Differential kg	Monte Carlo Method Percentage Difference %	Percent Improvement %
Single CTB 1	13.4	9.6	33	9.09	4.31	**32%**	0.54	**6%**	**27%**
Single CTB 2	13.4	13.4	58	11.40	2.00	**15%**	2.00	**15%**	**0%**
Singel CTB 3	13.4	13.4	58	14.82	-1.42	**-11%**	-1.42	**-11%**	**0%**
Single CTB 4	13.4	16.4	75	19.33	-5.93	**-44%**	-2.93	**-18%**	**26%**
Double CTB 1	24.5	24.5	57	13.76	10.74	**44%**	10.74	**44%**	**0%**
Double CTB 2	24.5	24.5	57	18.12	6.38	**26%**	6.38	**26%**	**0%**
Triple CTB 1	36.1	36.1	53	20.19	15.91	**44%**	15.91	**44%**	**0%**
Triple CTB 2	36.1	36.1	53	35.72	0.38	**1%**	0.38	**1%**	**0%**
Triple CTB 3	36.1	36.1	53	40.70	-4.60	**-13%**	-4.60	**-13%**	**0%**
M-01 1	63.7	63.7	55	49.64	14.06	**22%**	14.06	**22%**	**0%**
M-01 2	63.7	63.7	55	63.42	0.28	**0%**	0.28	**0%**	**0%**
M-02 1	51.5	24.3	5	37.51	13.99	**27%**	-13.21	**-54%**	**-27%**
M-02 2	51.5	29.9	10	43.74	7.76	**15%**	-13.84	**-46%**	**-31%**
M-02 3	51.5	40.0	33	50.10	1.40	**3%**	-10.10	**-25%**	**-23%**
M-02 4	51.5	40.0	33	54.08	-2.58	**-5%**	-14.08	**-35%**	**-30%**
M-02 5	51.5	51.5	55	58.64	-7.14	**-14%**	-7.14	**-14%**	**0%**
M-02 6	51.5	51.5	55	59.53	-8.03	**-16%**	-8.03	**-16%**	**0%**
M-02 7	51.5	51.5	55	62.88	-11.38	**-22%**	-11.38	**-22%**	**0%**
M-02 8	51.5	51.5	55	64.08	-12.58	**-24%**	-12.58	**-24%**	**0%**
M-02 9	51.5	51.5	55	64.38	-12.88	**-25%**	-12.88	**-25%**	**0%**
M-02 10	51.5	51.5	55	65.43	-13.93	**-27%**	-13.93	**-27%**	**0%**
M-02 11	51.5	51.5	55	66.15	-14.65	**-28%**	-14.65	**-28%**	**0%**
M-02 12	51.5	54.3	66	66.70	-15.20	**-30%**	-12.40	**-23%**	**7%**
M-02 13	51.5	54.3	66	66.78	-15.28	**-30%**	-12.48	**-23%**	**7%**
M-02 14	51.5	54.3	66	69.52	-18.02	**-35%**	-15.22	**-28%**	**7%**
M-02 15	51.5	61.5	75	71.37	-19.87	**-39%**	-9.87	**-16%**	**23%**
M-02 16	51.5	61.5	75	74.56	-23.06	**-45%**	-13.06	**-21%**	**24%**
M-02 17	51.5	75.1	90	76.75	-25.25	**-49%**	-1.65	**-2%**	**47%**
M-02 18	51.5	85.7	95	78.77	-27.27	**-53%**	6.93	**8%**	**45%**
M-03 1	108.0	108.0	58	114.90	-6.90	**-6%**	-6.90	**-6%**	**0%**
M-03 2	108.0	108.0	58	125.00	-17.00	**-16%**	-17.00	**-16%**	**0%**
TOTALS	**1481.3**	**1494.9**		**1612.4**		**-10%**		**-11%**	**3.2%**

These results are shown graphically in Figure 10. While negligible overall improvement was realized in this specific case, plotting the Monte Carlo-based predictions against the as-flown masses show that the general distribution is representative, just perhaps biased slightly low. This is consistent with the more recent M-02 packing data that shows these bags are being packed denser than the historical average.

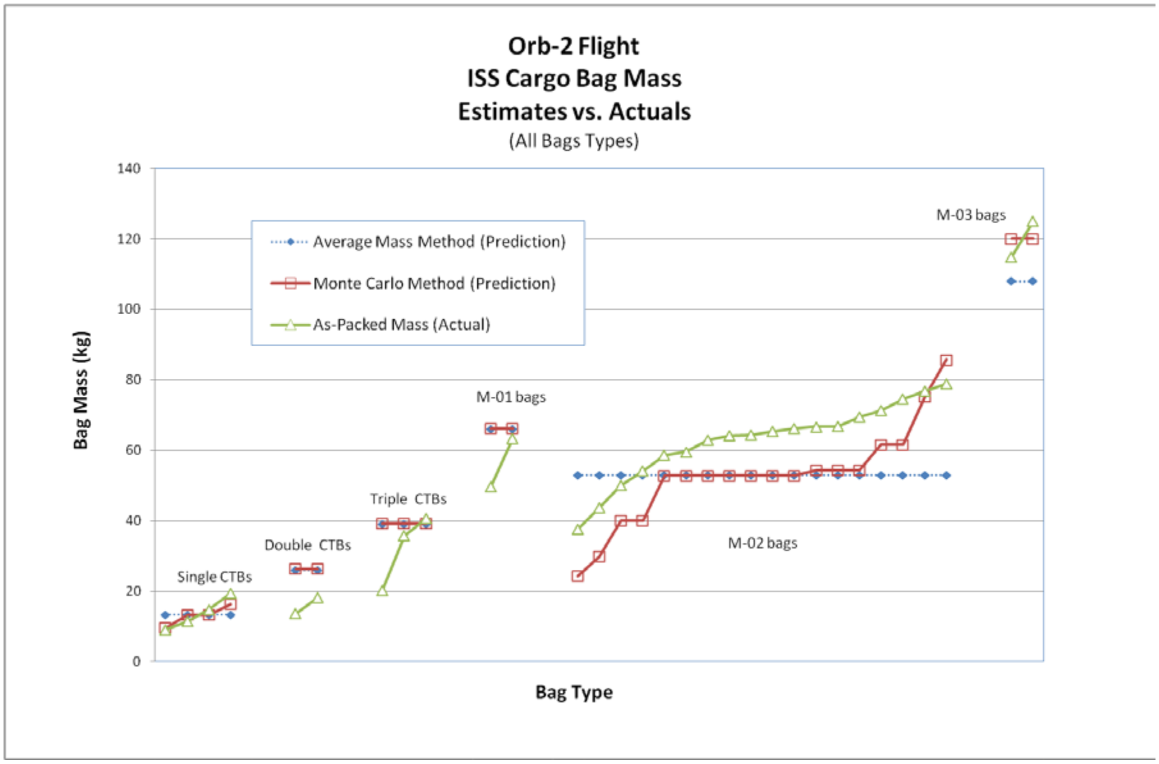

Figure 10. Orb-2 Preflight Predictions versus As-Flown Bag Masses

3. General Results

Sections 1 and 2 discuss the flight-specific results, but there are some general results that are applicable to both flights. The total mass for SpX-3 was predicted as 1109.2 kg using the average-mass method and 1137.3 kg with the Monte Carlo distribution method. These are at the 53rd and 65th percentiles for this bag complement based on the Monte Carlo simulation results for the total mass. The as-flown manifest, however, came in at 1358.7 kg, which is at the 99th percentile. Similarly, the Orb-2 flight predictions of 1481.3 kg and 1494.9 kg at the 52nd and 57th percentiles were much less than the as-flown manifest total of 1612.4 kg, the 87th percentile. Part of the shift for SpX-3 is attributable to the inclusion of the clamshell which was 73 kg heavier than the corresponding average M-01. The factor contributing to heavier mass of both flights, however, is likely the trend will be to pack bags more densely than the historical averages.

This was particularly evident in the Double CTBs on SpX-3 and the M-02s on Orb-3.

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VI. CONCLUSIONS AND RECOMMENDATIONS

This study performed the first detailed statistical analysis of ISS resupply cargo that can be applied in a meaningful way for the mutual benefit of NASA and the CRS providers. Some of these benefits were realized even before the completion of final analysis presented here. In 2014, NASA released a Request For Proposal (RFP) for the follow-on to the current CRS contract and in 2016 awarded new contracts to three providers, the two incumbents, SpaceX and Orbital, as well as newcomer, Sierra Nevada Corporation (NASA 2016). One area of emphasis for the follow-on contract was the desire to increase the cargo that can be delivered on the individual flights to alleviate the high volume of vehicle traffic at ISS. This will drive new spacecraft designs for both the incumbents as well as for Sierra Nevada. The detailed analysis of the historical cargo presented here formed the basis for the cargo related requirements in the RFP to accurately reflect NASA's resupply needs. Additionally, it allows NASA to provide the awardees with realistic densities and more representative notional manifests to help their partners in designing their spacecraft with the more robustness and flexibility.

A. CONCLUSIONS

This study has shown use of Monte Carlo simulation improves the accuracy of early cargo mass estimates for commercial resupply of ISS to a proof of concept level. With no preceding data for fully manifested commercial resupply flights, bag-level manifests based on Monte Carlo simulation results improved the individual bag mass predictions for Spx-3 by 16%, including a 25% improvement for the most prevalent bag, the Single CTB. A modest 3% improvement was shown for Orb-2, however, this is at least partly attributable to the recent trend of more densely packing the M-02 bags. Perhaps more importantly, the Monte Carlo derived manifest predictions for both flights more accurately represented

the distributed bag masses which is a critical factor for the CRS providers with respect to ballasting and other operational consideration for their spacecraft.

One aspect of this work that cannot be proven in this study but is valuable in practice is the use of the Monte Carlo simulation results throughout the manifesting process specifically dealing with intermediate deliverables. As the manifest matures, projected bags can be checked off against the predictions. The probabilities for the undefined bags, and the total mass, can then be quantified hence providing the basis for informed assessment of the risk of over- or under-shooting the predicted values. With these potential benefits the Monte Carlo derived approach can, and should, be matured for operational use to streamline resupply of ISS.

While this study has shown the potential to substantially improve the early bag-level manifest predictions, its true value will not be realized until it is put into practice and the desired effect of relieving the process is evaluated.

B. RECOMMENDATIONS

The manifesting process that existed when this study was first undertaken and described in Chapter I was so cumbersome and ineffective that it naturally evolved toward something resembling the work here. The new process includes some distribution of bag masses; however, this was not based on any statistical data, rather, it was mostly ad-hoc estimates and projections that relied on the experience of MIO personnel. This has generally improved the results but still requires near constant attention and interaction with the CRS providers. Understanding that, there is still much room for improvement by using Monte Carlo simulation derived estimates to streamline the process.

While this study yielded promising results at a proof-of-concept level, several improvements can be made to the simulation to increase its accuracy, and hence, is usefulness.

1. Update the Data

The underlying data for the simulation in this study dates back to 2001 and contains cargo delivered early in the ISS Program on Space Shuttle flights which may not accurately reflect the cargo needed for sustaining ISS for its remaining operational life. The first dedicated ISS resupply flight was ATV-1 launched in April 2008. Many dedicated resupply flights have flown since then and the body of as-flown cargo data for these vehicles has grown proportionately. Updating the historical data by removing the Shuttle flights and adding the dedicate resupply flights would provide a more representative body of data on which to base the simulation. Figure 11 presents the average bag density in kg/CTBE for each bag type for every dedicated resupply flight starting with ATV-1 through HTV-5, shown chronologically. Updating the data would allow recent trends like the increased packing densities, like those experienced starting at SpX-4, to be better represented. The data can be updated simply as flights accumulate and compared against the historical values to assess any other developing trends.

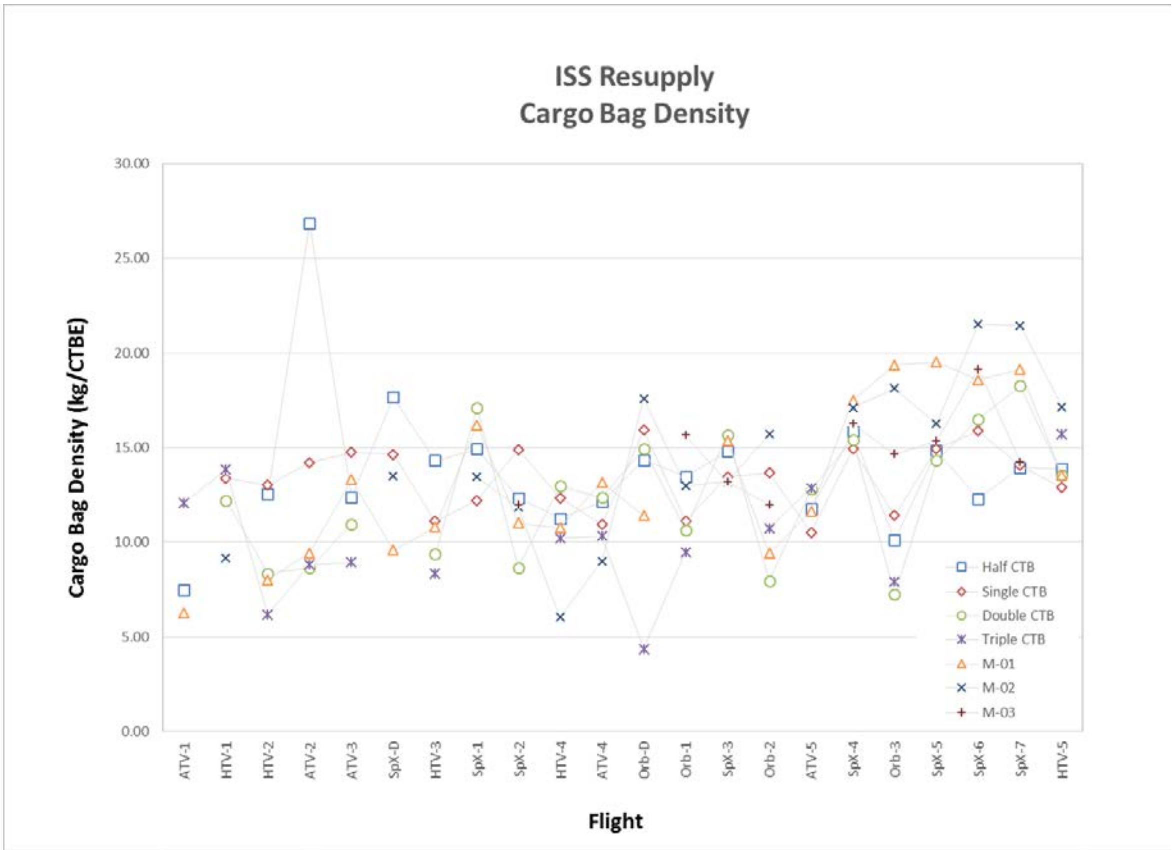


Figure 11. ISS Resupply Cargo Bag Densities

2. Find the Appropriate Distribution

A few key assumptions had to be made to investigate this as a potential improvement, the least of which was the distribution for the more prevalent bag types. In the absence of any preceding data for fully subscribed commercial flights, the “68-95-99.7” rule for normal distributions was loosely applied in constructing the manifests. Cargo data from flights of both Dragon and Cygnus flown since the fights investigated this study is now available that allows this assumption to be checked. The most populous bag for each spacecraft Single CTBs for Dragon and M-02s for Cygnus, will be examined.

a. SpX Single CTBS

Figure 12 is a scatter plot for the Single CTBs on flights SpX-3 through SpX-7 that shows the distribution on the bags for each flight. Visually, there does not appear to be any discernable pattern or consistent distribution.

Figure 12. Single CTBs on SpX-3 through SpX-7

The flight data was assessed using the single variable data fitting tool in Risk Simulator to determine if there were any consistent best fits across these flights. The results show that the assumption of a near-normal distribution was not far off as the normal distribution was the only distribution ranked consistently in the top five best fits using the Kolmogorov-Smirnov test statistic. The fits for these flight all had p-values above 0.8859. Table 18 shows the values for the raw data versus the values for the theoretical fit for the normal distribution fits for these flights. The mean of 13.4 kg from the historical data used the SpX-3 comparison was very close to the actual mean for the SpX-3 Single CTBs. This

average should be adjusted upward to reflect the increased packing densities going forward, which would be the case, provided that the underlying data was updated as recommended in Recommendation 1.

Table 18. Distribution Fits for Single CTBs on SpX-3 through SpX-7

Flight	Data Points	Data Type	Chosen Distribution	p-Value	Mean (kg)	Standard Deviation	Skewness	Kurtosis
SpX-3	17	Actual	--	--	13.46	6.343	0.28	-1.47
		Theoretical	Normal	0.9113	13.78	7.33	0.00	0.00
SpX-4	18	Actual	--	--	14.92	4.77	0.25	-0.71
		Theoretical	Normal	0.9390	14.68	5.70	0.00	0.00
SpX-5	18	Actual	--	--	14.94	5.53	0.42	-0.73
		Theoretical	Normal	0.9842	14.68	5.95	0.00	0.00
SpX-6	21	Actual	--	--	15.87	5.69	0.36	-0.65
		Theoretical	Normal	0.9875	15.49	6.19	0.00	0.00
SpX-7	23	Actual	--	--	14.05	5.22	0.26	1.43
		Theoretical	Normal	0.8859	14.07	5.80	0.00	0.00

b. Orbital M-02s

The same assessment was repeated for the M-02 bags launched on Orb-1 through Orb-6. The scatter plot in Figure 13 illustrates and increased packing density trend but no discernable distribution pattern.

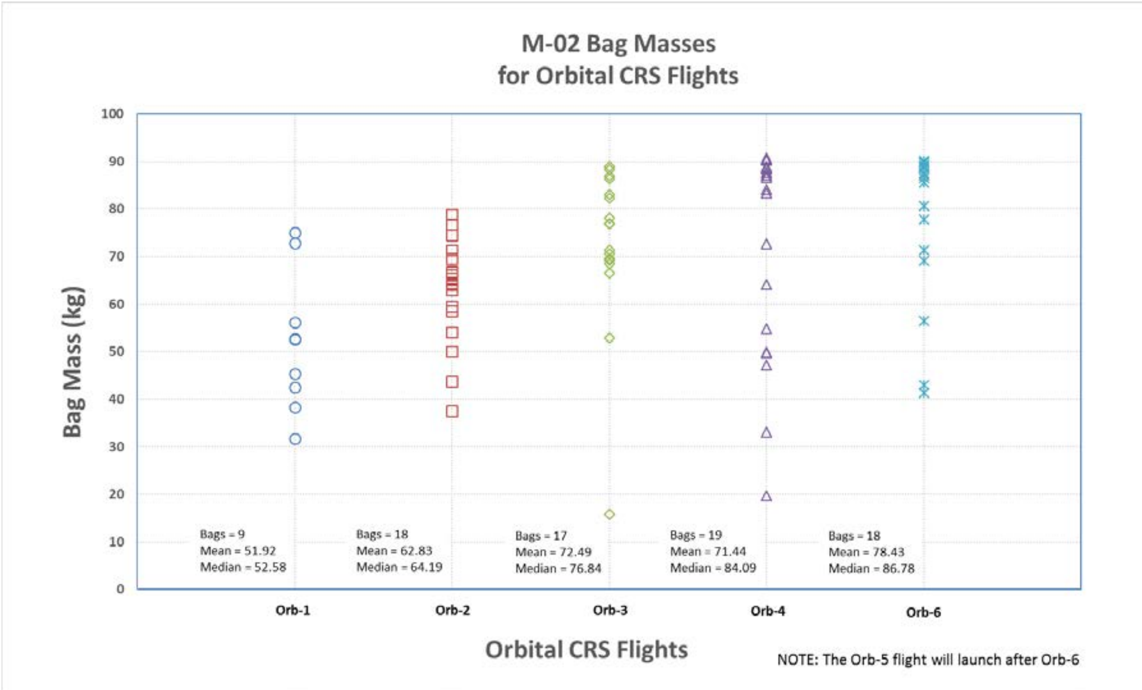


Figure 13. M-02 Bags on Orb-1 through Orb-6

This data was also checked in Risk Simulator's single variable fitting tool to find any common distributions. Normal distributions were found for the Orb-2 and Orb-3 data according to the Kolmogorov-Smirnov test statistic; however, the resulting curve fits for Orb-4 or Orb-6 account for less than 50% of the variation as the p-values for these flights were 0.3362 and 0.4958, respectively. One possible contributing factor may be the fact that these flights were flown after the failure of Orb-3 seconds after launch. In response, Orbital elected to launch these two flights on United Launch Alliance's Atlas V rocket while they investigated the root cause of the failure and redesigned their Antares rocket. Additionally, the cargo complement likely changed due to the need to recover from the cargo lost as a result of the failure. Without a consistent best-fit distribution across flights some discretion and judgment must be used for application for future flights. Data from Orb-5, when Orbital returns the newly-redesigned Antares rocket, may provide additional insight. Table 19 presents the

actual and theoretical distributional data for the Orbital flights. Parameters for both the best-fitting and normal distributions are shown for Orb-4 and Orb-6.

Table 19. Distribution Fits for M-02s on Orb-2 through Orb-6

Flight	Data Points	Data Type	Chosen Distribution	p-Value	Mean (kg)	Standard Deviation	Skewness	Kurtosis
Orb-2	18	Actual	--	--	62.83	10.92	-0.84	0.54
		Theoretical	Normal	0.9672	64.06	8.68	0.00	0.00
Orb-3	17	Actual	--	--	72.49	17.44	-2.31	6.85
		Theoretical	Normal	0.9914	74.98	10.95	0.00	0.00
Orb-4	19	Actual	--	--	71.44	22.39	-1.01	-0.15
		Theoretical	Cauchy	0.3362	NaN	NaN	NaN	NaN
		Theoretical	Normal	0.2194	74.40	22.39	0.00	0.00
Orb-6	18	Actual	--	--	78.43	16.06	-1.54	1.26
		Theoretical	PERT	0.4958	82.28	8.43	-0.91	0.45
		Theoretical	Normal	0.1540	79.62	16.06	0.00	0.00

3. Improve the Usability

NASA has historically performed tasks that were singularly unique to its human spaceflight efforts and there exists a general reluctance to use an automated tool for processes that are usually done by hand. Developing a user-friendly interface that streamlines the distributions of the bag masses for each type would go a long way in encouraging greater acceptance of this methodology. One possible approach could be a simple overlay that allows the user to define the number of the various types of bags, select the underlying input distributions, select the desired output distributions as a function of probabilistic percentiles, and enter any potential biases (heavy or light) to reflect recent trending. Such an interface would have the added advantage of being

able to be applicable to all existing and future resupply vehicle using the standard cargo bags.

C. AREAS FOR FURTHER RESEARCH

The wealth of available data made predicting launch manifests a natural candidate for the application of Monte Carlo simulation. Predicting return cargo manifests are as critical as launch manifests, if not more so. Knowing the total mass and the c.g.are fundamental elements in designing re-entry trajectories. Reentry analyses often begins with establishing a coordinate system with the origin at the spacecraft center of mass at the start of reentry. Not accurately knowing the c.g.location can result in errors in the reentry trajectory calculations such as those affecting deorbit burns. These errors can propagate into undershooting or overshooting the desired reentry corridor. Undershooting results in a steeper reentry that produces higher peak heating and dynamic pressures. Overshooting results higher heat loads which translates into the amount of heat that is ultimately transferred into the spacecraft's structure. Either of these errors can result in catastrophic consequences depending on the margins in the design of the spacecraft while both of these result in missing the desired landing area that can lengthen the recovery time.

There are a few notable challenges that complicate duplicating this investigation for return. The first is that not much return cargo data exists on which to base the simulations. The MPLM return cargo was not weighed or recorded with the same diligence as the launch data. Currently, only about one third of the launch mass is returned to earth via SpaceX, with the remaining two thirds being disposed through destructive reentry via Orbital, HTV, and ATV.

The second challenge is that while the return cargo manifest is well defined at the item level, the on-orbit packing process for return is not (and cannot be) as controlled as the packing for launch. Manifested return items may not fit in their designated bags and therefore may be packed in other bags. Standard pre-flight weights are used for the return cargo which may not be

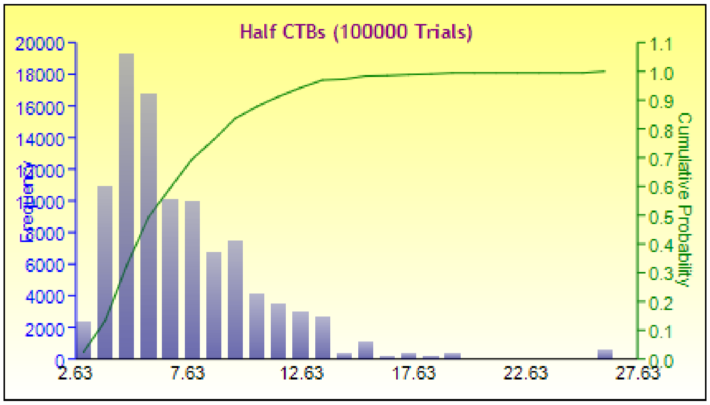
representative of the actual weight after the item has been used and/or processed on orbit. The ISS crew may use additional soft goods such as clothing to fill out the cargo bags and provide additional cushioning. Obviously, there's no final verification for the as-packed bag masses prior to return to Earth.

Even with these challenges, investigating the potential improvement through the application of Monte Carlo simulation as the body of return cargo bags masses accrues would be worthwhile endeavor.

APPENDIX. SIMULATION RESULTS BY BAG SIZE

This appendix contains the simulation results for the seven standard ISS cargo bag sizes in the form of histograms and the corresponding statistical data.

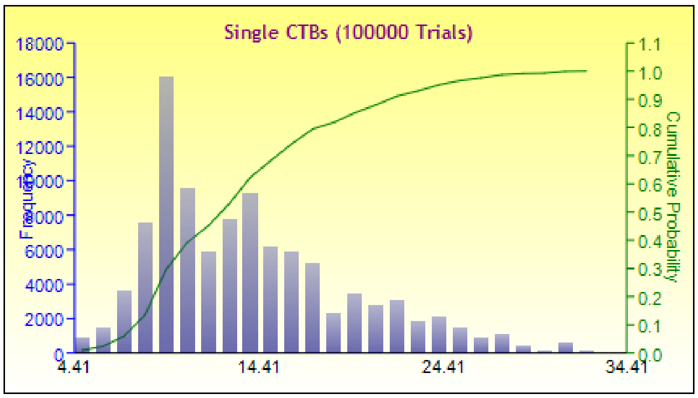
Half CTB Simulation Results



Type: Two-Tail, Lower: -Infinity, Upper: Infinity, Certainty: 100.0000%

Number of Trials 100000
Mean 6.8773
Median 5.9000
Standard Deviation 3.3170
Variance 11.0028
Coefficient of Variation 0.4823
Maximum 26.1600
Minimum 2.0000
Range 24.1600
Skewness 1.7708
Kurtosis 5.5268
25% Percentile 4.4800
75% Percentile 8.5900
Percentage Error Precision at 95% Confidence 0.2989%

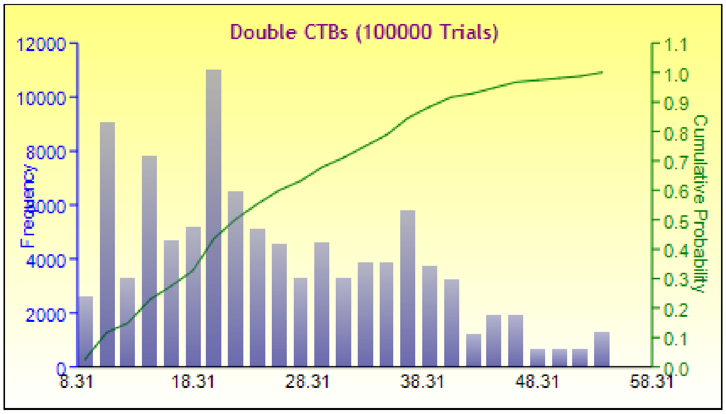
Single CTB Simulation Results



Type: Two-Tail, Lower: -Infinity, Upper: Infinity, Certainty: 100.0000%

Number of Trials 100000
Mean 13.3595
Median 12.2500
Standard Deviation 5.4413
Variance 29.6081
Coefficient of Variation 0.4073
Maximum 32.2100
Minimum 3.6700
Range 28.5400
Skewness 0.8890
Kurtosis 0.2968
25% Percentile 8.9900
75% Percentile 16.4000
Percentage Error Precision at 95% Confidence 0.2524%

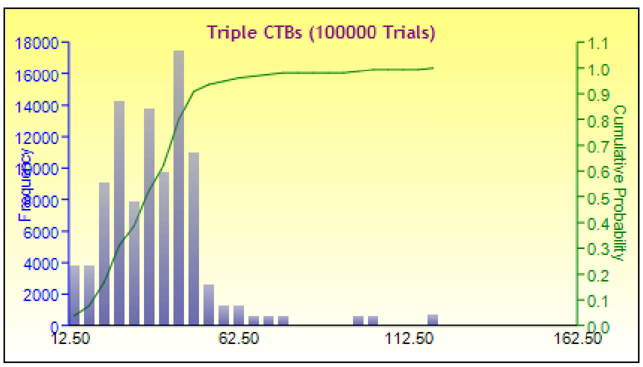
Double CTB Simulation Results



Type: Two-Tail, Lower: -Infinity, Upper: Infinity, Certainty: 100.0000%

Number of Trials 100000
Mean 24.4673
Median 21.8000
Standard Deviation 11.2618
Variance 126.8270
Coefficient of Variation 0.4603
Maximum 53.9800
Minimum 7.0900
Range 46.8900
Skewness 0.5134
Kurtosis -0.5674
25% Percentile 15.0800
75% Percentile 33.6600
Percentage Error Precision at 95% Confidence 0.2853%

Triple CTB Simulation Results



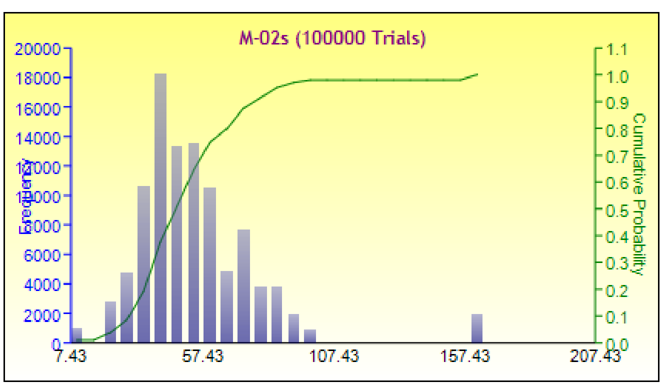
Type: Two-Tail, Lower: -Infinity, Upper: Infinity, Certainty: 100.0000%

Number of Trials 100000
Mean 36.0947
Standard Deviation 15.6689

Variance 245.5152
Coefficient of Variation 0.4341

Maximum 120.0300
Minimum 9.6300
Range 110.4000
Skewness 1.7795
Kurtosis 6.7884
25% Percentile 23.6500
75% Percentile 44.6500
Percentage Error Precision at 95% Confidence 0.2691%

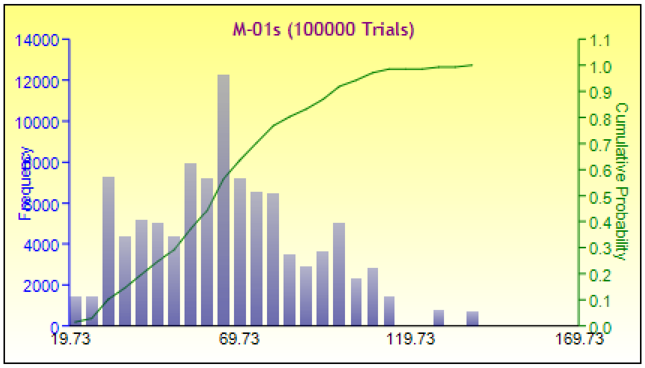
M-02 Simulation Results



Type: Two-Tail, Lower: -Infinity, Upper: Infinity, Certainty: 100.0000%

Number of Trials 100000
Mean 63.6720
Median 61.5400
Standard Deviation 23.8859
Variance 570.5372
Coefficient of Variation 0.3751
Maximum 138.2300
Minimum 16.5700
Range 121.6600
Skewness 0.3937
Kurtosis -0.1324
25% Percentile 46.5700
75% Percentile 76.7600
Percentage Error Precision at 95% Confidence 0.2325%

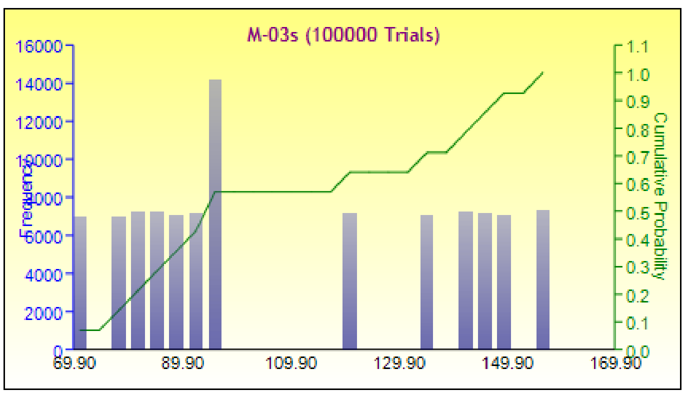
M-01 Simulation Results



Type: Two-Tail, Lower: -Infinity, Upper: Infinity, Certainty: 100.0000%

Number of Trials 100000
Mean 51.5050
Median 47.4100
Standard Deviation 23.2650
Variance 541.2622
Coefficient of Variation 0.4517
Maximum 162.3700
Minimum 3.2900
Range 159.0800
Skewness 2.0447
Kurtosis 7.6035
25% Percentile 36.6400
75% Percentile 61.5800
Percentage Error Precision at 95% Confidence 0.2800%

M-03 Simulation Results



Type: Two-Tail, Lower: -Infinity, Upper: Infinity, Certainty: 100.0000%

Number of Trials 100000
Mean 108.2358
Median 94.7200
Standard Deviation 29.6861
Variance 881.2629
Coefficient of Variation 0.2743
Maximum 156.5900
Minimum 67.5900
Range 89.0000
Skewness 0.3109
Kurtosis -1.4766
25% Percentile 82.9300
75% Percentile 139.3600
Percentage Error Precision at 95% Confidence 0.1700%

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